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AN OVERVIEW OF IEEE 693 – IEEE RECOMMENDED PRACTICE FOR THE SEISMIC DESIGN OF SUBSTATIONS

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SUMMARY

The paper describes the development of IEEE 693, the goals of the working group formed to produce it and its content. The intent is to provide a single set of seismic qualification requirements for the supply of substation equipment, and to encourage the integration of seismic requirements into the design of new equipment. The standard includes guidance on the seismic aspects of the installation of substation equipment, design requirements and the seismic qualification levels and methods to be specified by users for new equipment. As an adjunct to the development of the standard, participating utilities have initiated a program of testing to pre-qualify equipment and to gain experience in the use of the standard

INTRODUCTION

Before the introduction of IEEE 693 1997 most North American utilities provided their own unique set of requirements for the seismic qualification of new substation equipment. Manufacturers responded by trying to qualify their off the shelf products to meet the individual requirements and the resulting lack of consistency brought frustration and added expense to both suppliers and users. It was recognized that a standard that provided a single set of qualification requirements to which all utilities could refer in their specifications was needed.

HISTORY

A series of earthquakes in the nineteen seventies and eighties, notably the 1971 San Fernando (Mw = 6.6), the 1987 North Palm Springs (Mw = 6.1) and the 1989 Loma Priata (Mw = 6.9) caused major damage to substation equipment. It was apparent to both the utilities, who lost many millions of dollars in lost revenue and in repair costs and to the governments responsible for the affected areas that the seismic design of substations was woefully inadequate. As part of the effort to address these concerns a committee was struck under the chairmanship of Rulon Fronk of the Los Angeles Department of Water and Power to develop seismic qualification standards for substation equipment. The working committee consists of approximately fifty experts mostly from Canada, the United States and Mexico representing utilities, manufacturers, consultants, universities, and testing facilities.

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Very early in the process it was decided a) that the existing standard, IEEE693-1984 could be used as a starting point but that it required a complete rewrite, as it no longer reflected current knowledge and requirements b) that the document should be a recommended practice i.e. it should be considered voluntary, to facilitate it's acceptance by the Power Industry.

GOALS

IEEE 693 is intended as a single source document for the seismic design of substations. This is accomplished by either providing the information directly or referring the reader to the appropriate document.

Two goals have guided the work of the committee, to provide a clear "single set of requirements", and to encourage that seismic criteria be included in the initial design of substation equipment.

A Single Set of Requirements

The document must provide a clear single set of requirements which users can simply refer to in their specifications. The manufacturer then knows exactly what is required to qualify the equipment. e.g. The user states that the disconnect switch for example shall be qualified to the requirements of the "High Qualification Level". The manufacturer can pre-qualify it's equipment and there is potential to spread the cost of pre-qualification among several future buyers. It is not clear at present whether this expectation will be realized.

The manufacturer benefits because it now has order and direction. The user benefits since it can incorporate seismic requirements into the initial design of a substation knowing these will be met by the equipment specified. As will be shown later, the single set of requirements allows for various means of qualification by both analysis and testing.

This goal has been achieved, however it is recognized that there will be continued pressure within individual utilities to introduce other requirements specific to their needs. The value to the utilities of the standard will be reduced if this is allowed to occur.

Inclusion of Seismic Criteria in Equipment Design

Manufacturers design their equipment to meet functional requirements, electrical codes and standards. Many do not design for seismic requirements but endeavor to qualify the equipment to seismic criteria in response to customer's specifications. This may mean that the equipment has to be modified, by, as a last resort adding damping, or more typically by changing materials or increasing cross-sectional areas. The resulting increase in mass may however also increase seismic stresses. Including seismic requirements in the initial design is a more efficient approach and should result in a less costly piece of equipment more suited to a wider range of applications. This goal has not yet been achieved, however progress is being made particularly among those manufactures represented on the working committee.

CONTENT

Introduction

The American Society of Civil Engineers (ASCE) Guide to Substation Design [1]has been developed in parallel with IEEE 693 and together with the documents referenced in the two publications, form a comprehensive standard for the design of substations. IEEE693 includes the equipment and it's first support, and the ASCE guide covers most of the other structures in a substation with the exception of buildings and foundations. The first support is defined as the pedestal and support structure for a free standing piece of equipment, such as a disconnect switch or a surge arrester. For racks or A frames the first support is the member on which the equipment is directly supported, the remainder of the rack or A frame is designed using the ASCE Guide.

IEEE 693 provides design recommendations for the seismic qualification of the various types of equipment used in substations. The design recommendations consist of seismic criteria, qualification methods and levels, structural capacities, performance requirements for equipment operation, installation methods, and documentation.

The recommended practice is divided into nine clauses and twenty annexes. The clauses contain general seismic design and installation recommendations. The annexes contain equipment specific seismic design requirements. One annex is used to address requirements which are common to all equipment to minimize repetition, and one annex addresses the general requirements for equipment not otherwise specified.

Installation

Installation parameters can have a significant effect on the way equipment will respond and perform during an earthquake. Some of the equipment installation parameters can affect the motion of the equipment, they may accentuate or attenuate equipment response to an earthquake. The important installation parameters are equipment assembly, site response characteristics, soil-structure interaction, support structures, base isolation, suspension systems (such as wave traps), anchorage, and adjacent equipment interaction.

Two issues have been shown to require particular attention and are addressed in detail in the standard, the use of support structures and the interaction of adjacent equipment.

Support Structures

The support structure impacts the performance, accelerations and indeed the acceptability of the equipment. It may be acceptable on one support, but be unacceptable on another, and yet users have different support requirements. When equipment is being replaced, the user may wish to retain the existing supports. In some instances the support requirements are not known or may change after qualification has been done. It is therefore important to allow for these situations and to provide qualification procedures that can be used with a variety of supports. The standard lists cases that require the use of a support structure other than that used for the qualification, defines situations where modification of a support structure is required before qualification begins, and discusses situations in which the equipment can be qualified without a support. For the case where equipment is tested without a support, the shake table base acceleration shall be amplified to replicate the effects of the support, including the effects of translation, rotation, and torsional accelerations. The amplification value is then multiplied by 1.1 and applied during testing. When equipment is to be mounted on a support or supports and the parameters of the support are not known, then the qualification will be acceptable if the equipment is modeled or tested without a support and the qualification is conducted at two and one half times the requirements of the standard. The user shall then design the support so that it does not amplify the accelerations at the base of the equipment by more than two and a quarter times.

Interaction of Adjacent Equipment

Substation equipment is typically interconnected electrically with solid or flexible connectors. Equipment that is connected by conductors must have some provision in the installation that will allow for any relative deflection that will occur during an earthquake. Similarly, in rigid bus installation, it is necessary to incorporate adequate flexibility to permit axial or longitudinal movement of individual major equipment assemblies while avoiding the transfer of excessive forces between the individual components. While this subject is more fully addressed in a companion standard IEEE1527 [2], IEEE693 provides foundation information regarding conductor induced loading and installation. Based on analysis, tests, and forensic engineering after earthquakes, it has been determined that individual items of major equipment and bus supports move by varying degrees depending on their mass, mounting height, type and size of support structure etc. Typical equipment displacements are given at the three performance levels for equipment with three ranges of natural frequency. Guidance is given for the calculation of sufficient slack in conductors and in the use of various conductor configurations which incorporate slack while maintaining stability in cross winds and short circuit forces so as not to violate phase to phase and phase to ground air insulation clearances.

Qualification

The objective of the standard is to secure equipment that will not be structurally damaged and will continue to function when subjected to the ground shaking described by the required response spectrum (RRS) and equipment therefore is qualified by analysis or testing to the RRS. It is further anticipated that the equipment will perform acceptably after ground shaking up to the level of two times the RRS (Figs.1 and 2) with little or no significant damage and that most equipment will continue to function. However for reasons discussed later proper functioning may not always occur.

The RRS is a broadband response spectrum that attempts to envelope the effects of earthquakes in different areas, encompassing magnitude/distance combinations and considering site conditions ranging from rock to soft soil as described in the National Earthquake Hazards Reduction Program (NEHRP) – 1997. It should be noted that observed response spectra from some earthquakes exceed the RRS used in the standard. Different damping percentages are specified as shown in Figs. 1 and 2.

The RRS shapes bracket the vast majority of substation site conditions, and particular provides longer period coverage for soft sites. However very soft sites, and hill sites may not be covered by these spectral shapes. The user may develop and use a site specific response spectrum and be in compliance with the standard provided that the site specific spectrum envelopes the RRS' given.

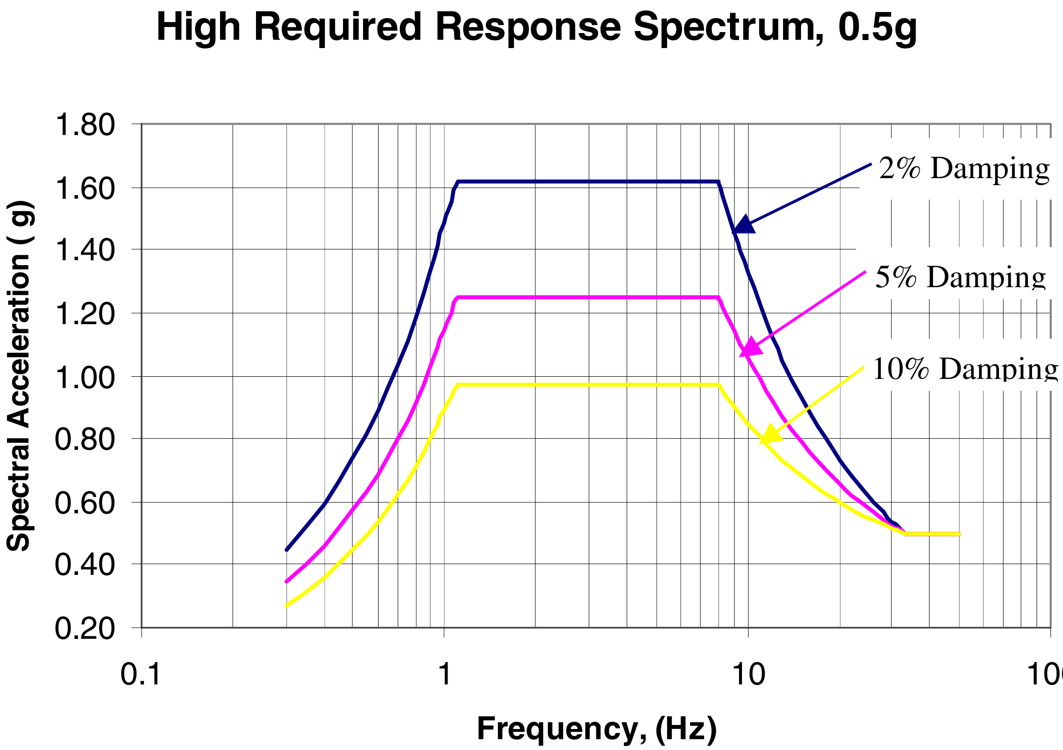
Qualification Levels

Since the anticipated loading due to earthquakes differs greatly from region to region, and in some cases there is an associated cost for meeting significantly higher seismic qualification levels, three seismic qualification levels have been established.

The levels are low, moderate, and high with the user determining the desired qualification level. Experience has shown that it is good practice to specify the same criteria for all like equipment in all substations within a reasonably large geographic area, even if some of the substations within the area have moderately higher or slightly lower expected levels of peak ground accelerations. This allows for interchangeability. Should equipment malfunction, or in the event of an earthquake fail, it can be replaced quickly with spare equipment or equipment from other substations. Keeping track of equipment and it's seismic qualification is also facilitated by maximizing the area over which the qualification applies.

The equipment performance implied by the qualification level is a level of ruggedness based on testing at lower levels combined with factors of safety for material, or analysis combined with experience from previous earthquakes. Thus the performance levels have a degree of uncertainly and the user may choose to select a qualification level higher than that based on site conditions to allow for other factors such as the equipment's criticality to its system.

The performance level for a site is determined by using either an earthquake hazard method or a seismic exposure map. The earthquake hazard method is preferred and can be use at any site, but the seismic exposure map method is an acceptable alternative.



Spectral Accelerations, S_a (Hz), for frequencies, f (Hz):

$S_a = 1.144\ \beta\ f$ for $0.0 \leq f \leq 1.1$

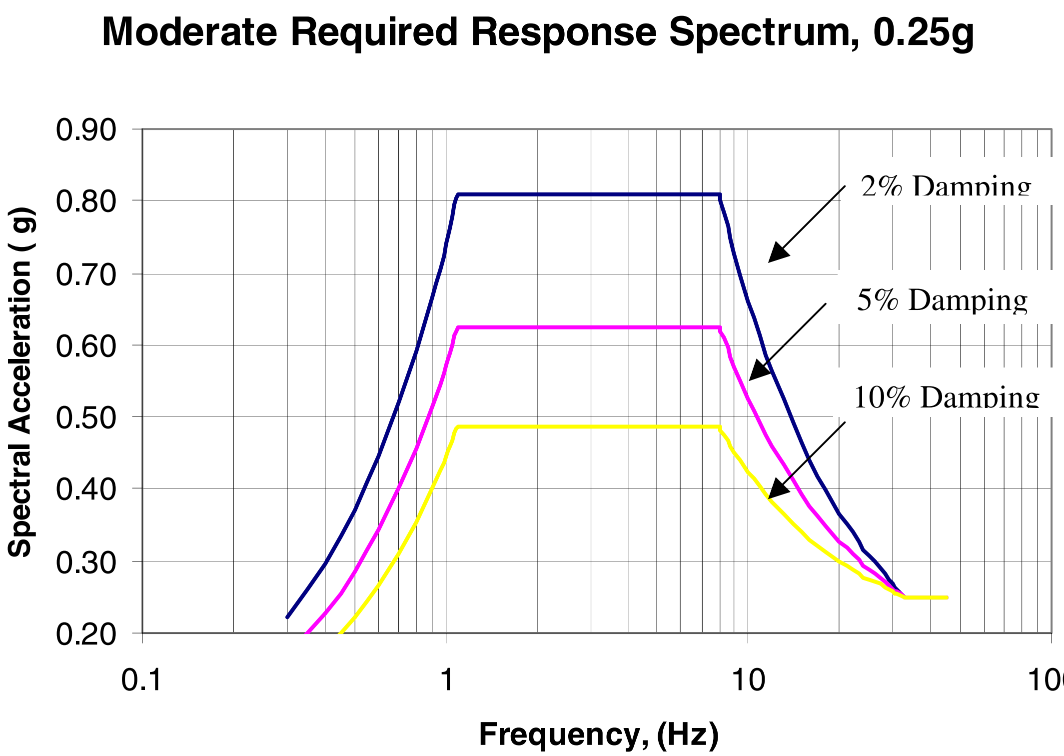
$S_a = 1.25\ \beta$ for $1.1 \leq f \geq 8.0$

$S_a = (13.2\ \beta - 5.28) / f - 0.4\ \beta + 0.66$ for $8.0 \leq f \geq 33$

$S_a = 0.5$ for $f > 33$

$\beta = (3.21 - 0.68 \ln(d) / 2.1156$ where d is the percent damping (2, 5, 10, etc)

Figure 1



Spectral Accelerations, S_a (Hz), for frequencies, f (Hz):

$S_a = 0.572\ \beta\ f$ for $0.0 \leq f \leq 1.1$

$S_a = 0.625\ \beta$ for $1.1 \leq f \geq 8.0$

$S_a = (6.6\ \beta - 2.64) / f - 0.2\ \beta + 0.33$ for $8.0 \leq f \geq 33$

$S_a = 0.25$ for $f > 33$

$\beta = (3.21 - 0.68 \ln(d) / 2.1156$ where d is the percent damping (2, 5, 10, etc.)

Figure 2

Earthquake Hazard Method
With this method the probabilistic earthquake hazard exposure of the subject substation is established using the site specific peak ground acceleration (PGA) developed in a study of the sites seismic hazard, selected at a 2% probability of exceedance in 50 years and modified for site conditions. If the PGA is at or

below 0.1g, then the level is classed as low. If the PGA is greater than 0.1g but equal or less than 0.5g the level is classed as moderate. If the PGA is greater than 0.5g the level is classified as high.

Seismic Exposure Map Method
This method uses the seismic exposure maps applicable to Canada (1995 NBCC), United States (NEHRP-1997) and Mexico (MDOC/CFE 1993) and modifies the 2% probability of exceedance in 50 years PGA given at the subject site according to soil type and foundation factors. Adjustments are also made to account for the different probability of 1995 NBCC map and for the higher seismicity of the west coast of Mexico. Again the results are compared with 0.1g, and 0.5g to establish qualification levels as above.

Performance Level
The performance level (PL) is the actual maximum ground level of shaking of the site. As discussed previously, the qualification is done at one-half of the PL or at the RRS. See Figure 3. The reasons for this are discussed below under performance factor.

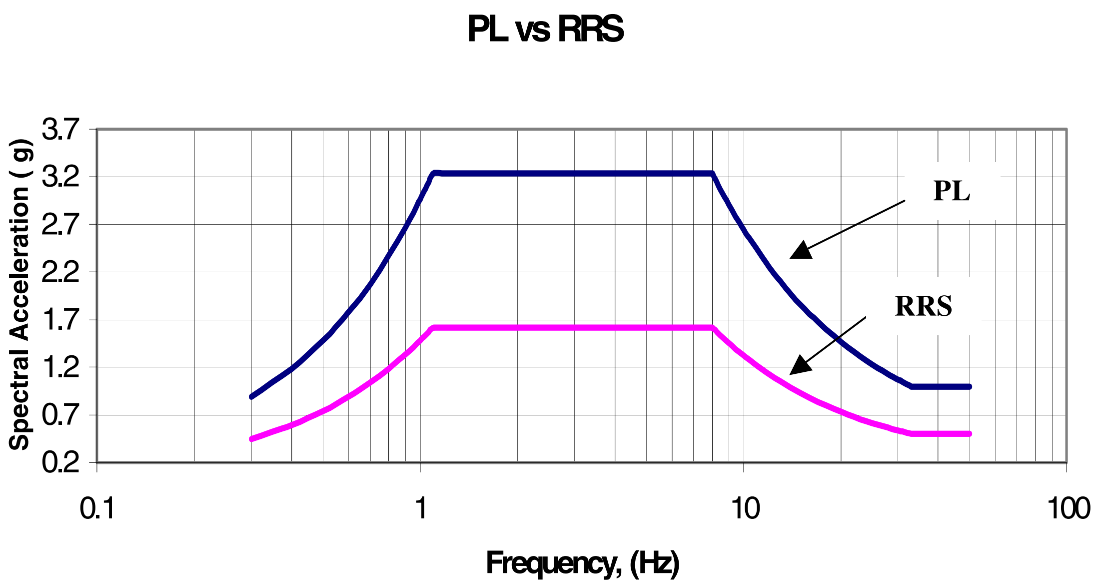


Figure 3

Performance Factor
The performance factor relates the response spectrum level at which the equipment is qualified by testing or analysis, that is the required response spectrum, to the maximum response spectrum level at which the equipment is expected to continue to be functional, that is the performance level. Thus, the performance factor times the RRS is the anticipated seismic capacity of the equipment. The standard establishes acceptance criteria so that the performance factor is 2. It would be preferable to test at least at the performance level but it may be impractical or not cost effective to test to this level for the following reasons:

a) Test laboratories may not be able to attain these acceleration levels, especially at low frequencies.
b) Since some yielding of ductile materials is considered acceptable at two times the RRS, some structural components may be damaged and would be a financial loss.

c) Testing to the theoretical limit of brittle materials, such as porcelain, may constitute an unacceptable safety risk
d) Equipment successfully tested to two times the RRS may not be acceptable to the user and therefore represents a financial loss.

The equipment may be tested at the RRS, with the projected performance factor demonstrated by means other than by direct testing. For consistency analysis is also to be performed at the RRS, with a performance factor applied. The projected performance factor that relates to the equipment test and analysis done to this standard results from allowable stress design. Equipment qualified by analysis and testing is evaluated against allowable stresses that typically vary from 50% of ultimate strength, e.g. for non ductile components to 80% of yield strength e.g. for ductile components. This method results in a calculated projected performance factor of two either directly or, when considering inelastic behaviour of the equipment and it's supports, or material over-strength. It is referred to as "projected" because there are inevitable uncertainties in the actual performance of equipment at the performance level. The actual limits of performance may vary from that defined by the projected performance factor due to the following:

a) An allowable stress is a function of the loading mechanism, loading combinations and material type. Consequently, a uniform projected performance factor is not expected, but it is anticipated from historical performance that these materials will be adequate at two times the RRS.
b) The natural variability in material strength allows for the statistical probability that components will perform at less or greater than expected capacity.
c) An increase in damping or energy dissipation due to inelastic behaviour. For most materials, the hysteresis damping capability increases at the higher levels of stress normally associated with higher levels of shaking.
d) If the locations of the highest stresses within the equipment are not identified and thus not monitored during the test or evaluated in analysis, the equipment may experience premature failure in an earthquake or when attempting to test at the performance level.
e) The response of the equipment to the dynamic loading or inelastic behaviour may be different at levels exceeding the RRS. If this is not anticipated, premature failures may occur.

Qualification Methods

Static analysis, static coefficient analysis, dynamic response spectrum analysis, load path evaluation, time history testing, sine beat testing, and static pull testing are methods used in the standard to qualify electrical equipment. The use of seismic response spectra as a means for qualifying equipment, either by calculation or by test, has become the most widely accepted and powerful method. Figures1 and 2 give the Required Response Spectra for High and Moderate Levels respectively. The maximum acceleration response of equipment occurs in the modes in the range of 1.1 Hz to 8Hz is as indicated by these spectra. The response levels are also a function of damping (the less damping the higher the response) Equipment vibration modes above 33 Hz are considered rigid and respond at the constant zero period acceleration (ZPA) of the response spectrum.

Whenever possible the equipment is to be analysed or tested in it's in situ or in service configuration including pedestal or other support structure. The effects of the electrical connections, conduit, sensing lines, and any other interfaces supplied by the manufacturer shall be considered and included in the analysis or test unless otherwise agreed. The equipment shall be analysed for the combination of dead, normal operating and seismic loads.

Analysis and time history testing is to be triaxial. The specified acceleration or RRS shall be applied independently in the two horizontal axes and in the vertical axis with specified acceleration or spectral acceleration of at least 80% of the horizontal value. Biaxial time history testing (one horizontal and vertical) may be used if it can be shown that no significant coupling exists in the equipment between the two horizontal axes to give additive responses in the unexcited axis or if the input acceleration is increased to account for any additive response.

Static Analysis
For equipment with a first vibration mode above 33 Hz simple static analysis can be used, applying a multiple of the ZPA at the centre of gravity in each principle axis direction and calculating the combined resulting stresses and anchorage loads.

Static Coefficient Analysis
This type of analysis usually applies to equipment having a few important modes of vibration in the range of frequencies normally found in earthquakes. A factor of 1.5 times the peak acceleration given in the RRS is applied according to the mass distribution of the equipment in the direction of each of the principle axes. The factor accounts for multimode effects.

Response Spectrum Dynamic Analysis
For complex structures with many vibration modes in the seismic range, a detailed finite element model is needed. The RRS method is used with the damping coefficient established by test or a conservatively low value (e.g. 2%) is used. It is also recommended that the lower frequencies of the mathematical model be verified by a simple bump or snap back test. The loads and modal stresses are then combined.

Time History Dynamic Analysis
This is a powerful tool when evaluating multiple, interconnected equipment or when studying complex equipment too large to test. This type of analysis is used only if a specific user requires it, since it requires a proper definition of the time history and is more expensive. This method is not used in IEEE 693. The analysis can be applied to a finite element model having both linear and to non linear elements where important non linearities in equipment behaviour require study.

Time History Shake Table Testing
It is most important that the calculated test response spectrum (TRS) of the table motion at the test facility envelopes the RRS in a manner similar to that of an actual earthquake. That is, it envelopes the RRS with amplitudes frequencies, and energy levels that occur in a similar simultaneous manner. If all the resonances of the equipment have been definitely been established it is sufficient that the TRS envelopes the RRS at and above the first mode frequency. The TRS is to be computed using a damping ratio at or above that of the RRS and shall include at least 20 seconds of strong motion.

The method of attaching equipment to the test table should be as far as possible the same or equivalent to that used on the in service foundation or supporting structure. Strain gauge bolts are recommended to measure anchorage loads.

The locations at which strain gauges are attached to the test specimen are of critical importance. As discussed, equipment is tested to half the level of shaking at which it can reasonably be expected to survive in an earthquake. Qualification then relies on extrapolating the stresses measured to establish the anticipated performance and if the strain gauges are not located at positions of maximum stress the seismic performance of the equipment will be overestimated.

Prior to shake table testing of composite insulators and bushings a horizontal load of half the specified mechanical load (SML) be applied to the top of the specimen in the direction of the shake table tests and the resulting deflection measured. After the shake-table testing is complete, the test done prior to testing is repeated and compared to the first test data. The difference in data determines passage of the qualification.

The correct function of some equipment is proven during the strong motion of a shake table test as appropriate. e.g. circuit breakers are operated during the test.

Equipment that is qualified by testing according to the standard to twice the RRS is said to meet the performance level. Testing to this level is an optional method of qualification and will provide higher assurance that the equipment will function after experiencing and earthquake with a response spectra up to twice the RRS.

Sine Beat Testing
While the time-history test is intended to apply multimode frequencies as do actual earthquakes, the sine-beat applies one frequency at a time. The frequencies chosen are the resonant frequencies of the equipment and its support. This test almost always is more severe than the time-history test, because it is at the equipment and supports resonant frequencies. It has been noted that earthquakes do dwell on a single frequency much as the sine-beat does. This test is required when it is important to demonstrate that equipment sensitive to this type of vibration can survive this type of loading.

Static Pull Testing
The static pull test consists of pulling the equipment in the direction that provides the most severe loading with a load that is two times the weight of the equipment.

Load Path
It is necessary to ensure that there is a properly designed load path through equipment to the foundations. The load path is the route the loads follow through the equipment to the foundations. This particularly applied to equipment that incorporates otherwise inherently rugged multiple components such as a transformer. Such equipment can be accepted as qualified as long as there is a clearly defined and adequately designed load path. Among the forces that are to be considered are seismic (simultaneous triaxial loading), gravitational, and normal operating loads. The load path shall not include the following

a) Sacrificial collapse members.
b) Materials that will undergo non-elastic deformations, unrestrained translation, or have rotational degrees of freedom.
c) Solely friction dependent restraint

Optional Qualification Methods
Qualification methods have a hierarchy. Some methods provide better assurance that the equipment will indeed be able to withstand the earthquake it is designed to withstand. That is, equipment that is known to be rugged, are less important to the function of the substation and generally survive earthquakes need not be qualified by the same rigorous means as equipment that are known to fail in earthquakes and are important to the function of the substation. Analysis for instance can give insufficient attention to parts of the equipment that are in fact critical to its seismic performance, whereas testing may identify weaknesses not identified by analysis.
Generally the hierarchy is, from best assurance to least:

1 Testing (time history and sine beat)
2 Dynamic Analysis
3 Static Pull Test
4 Static Analysis
5 Load Path

IEEE 693 allows suppliers to qualify equipment using methods that provide better assurance than those specified in the standard, at their option. Further the supplier has the option to use greater accelerations than specified and when testing is specified, testing to the performance level, i.e. at twice the RRS.

Functionality of Equipment

The ultimate requirement for equipment is to be capable of functioning before, during and after an earthquake. This can only be fully verified by testing to a level equivalent to the particular earthquake and performing the required functions before, during and after the test. Switches, linkages, relays etc. must remain functional, or must change state as required to perform their function. Both mechanical and electrical integrity requirements are to be met. Functional tests of some equipment types are required in the standard during tests to the required response level. Functionality can only be demonstrated by testing and can only be demonstrated to the maximum level of expected ground shaking by testing to the PL level.

Special Cases

Manufacturers may choose to test beyond specified requirements (over-testing), broadening the specification to include a wide variety of applications. While such testing can lead to severe test motion and potential equipment damage it can also lead to improved seismic design. Similarly deliberately testing to failure, fragility testing, can be used to determine the ultimate capability of equipment. Such testing serves to prove adequacy for more extreme earthquake impact and may conclusively identify weak points in the equipment, leading to improved seismic capability. Such testing provides useful information on the seismic margin of the equipment performance over that proven by testing at the required response level.

Some substation structures are too large to test, e.g. capacitor platforms, however a degree of on site testing can be accomplished using portable shaking devices. This testing has the advantage of including the complete structure and to some extent the foundation and soil effects but the motion is not typical of earthquake random type motion. The results can be used however, to update and improve the accuracy of analytical models. Similarly snap back tests (in which a structure is deformed and then released) can be used to confirm assumed damping characteristics used in analysis.

Qualification by Seismic Experience Data

Procedures for qualifying certain equipment through the use of actual earthquake experience have been developed in the nuclear power industry. The use of earthquake experience data as a qualification method is also addressed in IEEE Std-344 [3]

Earthquake experience data typically applies to categories of equipment rather than to specific items. The documented performance record of the equipment category must demonstrate that there is no tendency for significant structural damage over the range of ground shaking experienced in earthquakes. The record consists of an inventory of equipment within the particular category that has experienced substantial earthquake ground motion, for which the post earthquake condition of the equipment has been verified.

Design Requirements

IEEE 693 specifies various design requirements for substation equipment.

Support Frames

Requirements for the design, materials, workmanship, fabrication and detailing are given by referencing relevant standards. The support frame shall be designed to minimise deflections.

Anchorage to Concrete

Attention is given to equipment anchorage particularly since it has been found to be a significant source of failure during earthquakes. The anchorage requirements of equipment to concrete assemblies including welds and anchor bolts is specified with the manufacturer supplying the design while the user or it's agent does the installation. For anchor bolts, the size of the hole provided in the equipment must be the correct size for the bolts. A minimum of three quarter inch diameter anchor bolts are required unless a safety factor of two can be demonstrated. Minimum bolt sizes are recommended to allow for corrosion of the bolts that are normally hidden from view. A307/A36 bolts are requires as opposed to higher strength bolts since their ductility allows for better survivability during shock loading.

Structural Bolts and Steel

The maximum ultimate tensile strength (UTS) of bolts to be used is limited at 965 MPa and the yield strength of structural steel is limited to 650 Mpa. Bolts with a UTS of 965 MPa or greater are known to have very poor repetitive load carry capacity. Structures with these bolts have been shown to have lost capacity due to wind loading and unloading.

Testing Consortium

A consortium of ten electrical utilities, organized under the Electric Power Research Institute is working with manufacturers to qualify equipment by testing. This work has allowed participating manufacturers to pre-qualify equipment and become familiar with the requirements of IEEE 693. It has afforded an opportunity for both the utilities and the manufacturers to further understand the behaviour of equipment tested to the required levels and in some instances beyond this level. Experience gained has been reported to the working group and considered for incorporation into the next revision of the standard.

REFERENCES

1. IEEE Std 605 ASCE Substation Structure Design Guide
2. IEEE Std 1527-2003, Recommended Practice for the Design of Flexible Buswork Located in Seismically Active Areas.
3. IEEE Std 344-1987 (Reaff 1993), IEEE Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations