Seismic Considerations of Circuit Breakers

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Abstract: The tutorial covers the seismic qualification of high voltage power equipment using IEEE 693. The application of the standard will be illustrated using high voltage power circuit breakers. The tutorial will also give the substation engineer and end users examples of breaker design features which provide the highest seismic withstand capabilities.

Keywords: Seismic, Earthquake, Seismic Qualification, Circuit Breaker, Response Spectrum, IEEE std 693, Seismic Design, Shake Table.

General

The title of the IEEE 693 standard, “Recommended Practice for Seismic Design of Substations,” would be more descriptive as the “Seismic Qualification of High Voltage Power Equipment” which is the primary content and purpose of the document. The standard does contain some general guidelines for the substation design but directs you to the International Building Code (IBC) and the American Society of Civil Engineers (ASCE) Substation Structure Design Guide for the civil engineering design of the substation structures, foundations and anchorages.

The document focuses on the high voltage power equipment such as the breakers, transformers, disconnect switches, instrument transformers, reactors, circuit switchers and arresters. The large high voltage equipment has been the most problematic in seismic events and is the most difficult to replace when damaged. The standard is not so much a guide on how to design the equipment to resist the earthquake but instead defines the qualification process for seismic test or analysis to insure they survive a seismic event and maintain function. The standard is based on many years of west coast seismic experience and depends more on shake table tests than analysis to most reliably insure that a piece of equipment will have acceptable seismic withstand capability.

The seismic qualification process

1. The direct way to get started with applying IEEE 693 is to go first to figure 1 in the standard, “Using this recommended practice,” for a flow chart or quick overview of the document.

![Seismic Design of Substations](image)

Figure 1 - Using this recommended practice (1)

2. Follow the right branch of the flow chart to find the first step in the process which is to select the seismic qualification level of low, moderate or high. The 2005 version of the standard has qualification levels in Clause 8. You will likely already know which seismic qualification level applies to your region. Generally, the high level is required out west and the moderate level applies to active seismic zones in the eastern and central states.
3. Move down to the next box to find the Annex for your specific equipment type. The qualifications procedure for your equipment is given according to the voltage rating.

**Seismic Qualification Levels:**

Earthquakes events are generally defined by intensity and magnitude. Intensity, such as the Modified Mercalli scale is used to give a subjective description of the earthquake’s affect. The Magnitude scale gives a quantitative measure of seismic events based on the amplitude of motion recorded by a seismograph. For design and test purposes we need a more specific definition of the seismic event which can be related to the dynamic acceleration that the ground applies to our equipment.

The highest intensity and magnitude seismic events have peak ground accelerations over 0.5gs and some may reach 1g. These accelerations can be applied horizontally as well as vertically to the equipment and may cause even higher dynamic response accelerations in the equipment. The problem arises because high voltage equipment may have resonant or natural frequencies close to the frequency of the seismic waves traveling through the ground during an earthquake. Repeated cycles of the resonant frequency can cause the equipment accelerations to build up to 2 or 3 gs. Effectively this means that up to three times the weight maybe applied horizontally to center of mass of the equipment or to parts of the equipment. For tall, heavy high voltage equipment, this may cause failure of the foundations, supporting structures or high voltage insulators. A careful study of stresses along the load path from the foundation to the top of the equipment is needed to insure the equipment can resist high seismic accelerations.

Seismic zone or hazard maps are used to give the peak ground acceleration. The building codes such as the IBC contain such maps and the standard discusses how to apply these to determine the appropriate qualification levels for Canada, the US and Mexico. For the US, seismic hazard maps are available for download at USGS.gov. Figure 2 is the overall USGS map for the US.

The equipment Annex will direct you back to other applicable sections as they are needed to define the analysis or test methods and acceptance criteria in detail.

The most important tool that we have for seismic design and qualification is the response spectrum. The response spectrum is a graph of the response acceleration of single degree of freedom oscillators, all with the same damping, to the same ground acceleration. For the high seismic qualification level, which has a peak input ground acceleration of 0.5g, the required response spectrum (RRS) for is given in figure 3.

![Figure 3 – High required response spectrum, 0.5g](image)

The response spectrum is the theoretical response of the equipment and its components which have the resonant frequencies and damping given in the curve. In dynamic analysis, the response spectrum can be used to calculate the response accelerations of equipment. In testing, the shake table acceleration (not the equipment response acceleration) is converted into a test response spectrum (TRS) which can be compared to the RRS to ensure that an acceptable magnitude and frequency content of the input motion was applied.

The Figure 3, RRS, has a broadband (1 to 8 Hz) response of 1.6gs (at 2% damping), to the 0.5g peak ground acceleration, due to the amplification from multiple ground oscillations which can occur within this frequency range. The broadband RRS is intended to cover a wide range of earthquakes rather than just to represent a single recorded event for a major earthquake. If the equipment has no resonant frequencies below 33 Hz, then it is effectively a rigid body without increased response acceleration, and experiences only 0.5gs (the zero period acceleration).

The standard has simplified the qualification process by condensing the requirements into three levels. The first level is basically for very low seismic zones and has no specific analysis or test requirements. The other two have very detailed analysis and test requirements to meet the qualification level.
The three seismic qualification levels are:

1. **Low - 0.1g or less.** This value roughly corresponds to the 0.2 G static horizontal seismic load in ANSI C37.09 for design and test of high voltage insulators and bushings.
2. **Moderate - 0.25g.** This value has generally been applied to lower acceleration and the less active seismic zones of the eastern and central US. The moderate required response spectrum is 50% of the RRS given in Figure 3.
3. **High – 0.5g.** This level has been generally applied to the very active and high seismic areas of the west coast.

**Projected Performance Level:**

In the seismic qualification requirements, brittle materials such as porcelain must not exceed 50% of the ultimate (breaking) strength and ductile materials such as steel must not exceed about 60% of the yield strength. Therefore, the intent of the high level qualification is to achieve a projected performance level which is twice the RRS or for 1g.

Figure 4, plots the response spectra for the Loma Prieta earthquake of San Francisco in 1989, the Northridge earthquake of Los Angeles in 1994 and the Kobe, Japan earthquake of 1995. From the data, it is evident that the 1g performance level is needed for these high seismic locations.

The response spectrum for the high performance level is also plotted in Figure 4 to show that it envelops these strong earthquakes. Equipment designed to the required stresses and tested to the high performance level may experience slight yielding of ductile steel structures but it should not fail.

The 0.5g sine beat test is represented by the top line with the 5g response acceleration for 2% of critical damping. The 0.5 sine beat test is required for the high level qualification (and 0.25 g is required for the moderate qualification level) of circuit breakers. It is applied at each discrete resonant frequency, one at a time, rather than as a broadband time history input as used to test to the RRS. However, it does demonstrate very strong structural robustness of the equipment and gives further evidence that the 1g performance level may be achieved.

You may ask, why not test to the 1g high performance level? The problem is that size and weight of large equipment may exceed the shake table capabilities to reach 1g and in some cases it is every very difficult to reach the 0.5g RRS at the low frequency end of the spectrum. However, if possible, it is desirable to test to twice the RRS. Testing to the 1g performance level will not only prove the strength of the equipment but also its ability to maintain operation and function during and after such a strong seismic event.

**Seismic Design Features:**

The standard does give some guidelines on design of anchorages and installation considerations such as the terminal deflections in Clause 5. However, it is up to the designer/manufacturer to determine how best to design and build their products to meet the seismic qualification level of the standard. Following are some examples of good design features which have been proven over the years in circuit breaker design.

**Good Seismic Design Features:**

1. Avoid stress concentrations in the load path.
2. Reduce weights and moments of equipment.
3. Use composite bushing insulators instead of porcelain.
4. Use high strength insulation supports in the interrupter.
5. Avoid bending loads in connections to critical components such as the tanks or housings.
6. Keep higher stresses in ductile components along the load path and reduce stress in brittle components to increase damping and improve seismic toughness.

The seismic response acceleration creates inertial loads due to mass of the equipment. The load must be resisted by all elements in the load path down to the anchorages and equipment foundations. Each element in the load path from the bushings to their attachment to the housing or tank and into the support structure, anchorages, and foundation must be considered.

Careful design can increase the strength by reducing stress concentration and bending in the flanges, bolted joints,
welds and support points along the path. Avoid adding stiffeners, gussets or ribs in flanges or tank shells which can create high local stress concentrations in cast and welded components. Instead, increase the thickness of the flange or shell to have a stronger and tougher seismic design.

In testing to the qualification level, strain gauges should be applied to each critical point along the load path to insure the highest stresses are measured.

Reduced weights and moments can be inherent in good seismic design. For example a dead tank breaker which has the interrupter mounted inside a tank at the ground level rather at the top a tall insulating column has a major advantage in reducing moments and seismic stresses. Aluminum tanks and housings are lighter than the older steel tank designs. Likewise, composite bushings are typically less than half the weight of porcelain and can greatly reduce the bending moments applied during an earthquake.

In the very large EHV breakers, the connection point from the interrupter tank to the steel support structure can be improved by using a pin connection rather than bolts as shown in Figure 5. The pin connection eliminates local bending stress in the tank shell from the high overturning moment in the side-to-side or narrow direction of the support structure. The bending reaction in the steel structure is not transferred to the tank shell through a pin since it is free to rotate. This type of connection will increase the overall toughness of the breaker under extreme loads to prevent damage to the tank. The bending in the bolted steel structure will have the added benefit of generating increased damping which will reduce the overall seismic reactions in the tank and bushings.

Seismic Qualification by Testing

The primary qualification method for circuit breakers is to perform full scale seismic tests on a shake table. The shake table motion is controlled to simulate an earthquake time history and to meet the RRS test level. Analysis is accepted for 145 kV and for lower voltages, since the seismic experience has been very good for the smaller breakers. However, the 169 kV and higher voltage breakers, require testing for the moderate and high qualification levels.

The test qualification procedure is conducted in stages:

1. Initial cantilever vs. deflection test for composite bushings.
2. Initial resonant frequency search.
3. Time history test to envelop the RRS, in the closed position.
4. Time history test to envelop the RRS, with an OCO operation near the middle of the shake.
5. Sine beat test at each resonant frequency.
6. Repeat resonant frequency search to check for change.
7. Repeat cantilever vs. deflection test for composite bushings to check or change.

Figure 6 shows a 242 kV rated dead tank breaker mounted on a shake table. The breaker is instrumented with accelerometers on the bushing tops as shown in Figure 7 and on the tank top (near the center of gravity) as shown in Figure 8. Accelerometers were also located on the shake table, interrupter, operating mechanism and on the relay control panel to measure their response accelerations.

Figure 6 – Breaker on shake table

Strain gauges were located on the base of the bushing to measure cantilever bending loads and on the tank nozzles at the shell intersection to measure the maximum stress. The bushing strain gauges had been calibrated by
cantilever load test prior to the seismic test to closely monitor loads on the pressurized porcelain throughout the tests to prevent failure and to insure safety.

Additional, strain gauges were attached to the tank mounting flange, the mounting bracket and the structural steel support frame at the top beam and at the legs. Load bolts were used to attach the legs to the shake table. The load path was instrumented from the top a bushing on the center phase and the top of a bushing on an outside phase through the tank and support structure to ground.

The interrupter contacts and control circuits were monitored for contact bounce during the test.

The pretest and post test inspections of the breaker included production tests such as measuring terminal-to-terminal contact resistance, timing of the breaker, leak tests and then high-potential testing when the breaker was returned to the factory.

When testing to the RRS, the stresses must not exceed 50% of the ultimate stress for brittle materials or 60% of the yield stress for ductile material. The breaker must demonstrate proper operation during and after the seismic test and there should be no damage visible or detected by the standard production tests.

If any weakness, high stresses or malfunctions are found during the testing, improvements should be made while still in the lab, if possible, and then the change should be retested.

Seismic Test Qualification Documentation

The seismic qualification should be documented by:
1. Test plan
2. Test report with data tables
3. Test video
4. Seismic outline drawing
5. Nameplate with seismic qualification level

The seismic report should include the test plan and test results in a report following the format in the standard. The
The test report should cover the details of the equipment as tested. The instrumentation locations should be shown by diagrams or photos. The time history accelerations, stresses and deflections should be tabulated. The sine beat frequencies, modes of vibration, stresses and damping should be tabulated. The results of the pre and post tests and functional test should be presented. The plotted test response spectrum and recorded data from the instrumentation should be provided in an appendix.

The seismic outline drawing for the equipment should contain the weight, CG, the seismic response data of resonant frequencies, damping, deflections and foundation loads. The seismic qualification level and method should be stated.

In addition, the test plan, test report and seismic outline drawing should be approved by a qualified specialist with seismic training and experience in seismic testing of electrical equipment. A registered professional engineer is preferred.

The equipment should have a seismic qualification tag or nameplate permanently attached to it to list the seismic qualification standard, qualification level and qualification method.

References:

(1) IEEE std 693-2005, Figure 1, page 3.
(2) IEEE std 693-2005, Figure A.1, page 52.
(3) http://earthquake.usgs.gov/research/hazmaps/products_data/images/nshm_us02.gif

Biography:

Willie Freeman is the Chief Engineer at ABB High Voltage Products in Mt. Pleasant. He has over 35 years of experience in the design and development of high voltage switchgear and other equipment. Previously, he held design engineering positions at the Westinghouse Power Circuit Breaker and Machinery Technology Divisions. He holds MSME and BSME degrees from the University of Pittsburgh and Georgia Tech, respectively, and is a licensed professional engineer.