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SEISMIC QUALIFICATION: AN APPROACH FOR SAFE POWER SYSTEM DURING EARTHQUAKES

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Abstract

Earthquakes have caused many catastrophes in the past. Construction industries, electrical industries and people should be aware of the danger and prepared against earthquakes by constructing earthquake resistant structures. Past earthquake data reveals electrical and telecommunication facilities are seismically vulnerable and susceptible to failure due to seismic dynamic loading. High voltage substation equipments are most vulnerable in electrical and telecommunication facilities. Demand for electric power supply during post-earthquake and safety of consumers emphasize the need for seismic reliable electrical power system. For reliable power supply during and after earthquakes electrical equipment shall be seismically qualified before installation. Basics of seismic qualification of electrical equipment, procedure of qualification and relevant codal provisions are presented in this paper.

Keywords: Seismic qualification; Natural frequency; Electrical equipment; Substation equipment; Damping; resonance

1. Introduction

Instant release of energy accumulated at the geological faults results in earthquakes. Crust layer of earth vibrates in three directions simultaneously during earthquake. Earthquake vibration is random in nature with frequency content less than 33 Hz and with high energy content at lower frequency. The consequences of earthquake events are loss of life, huge damage to the civil buildings, destruction of the infrastructure, damage to the cultural heritage resulting in large cost to restore cities to their original state. This results in business interruption, loss of revenues, interruption of industrial production. The reliability and safety of electrical power system after earthquake rely on the seismic stability of individual substation equipment such as instrument transformers, surge arresters, transformer bushings, switchgears etc.

Past data collected post-earthquakes all over the world reveal massive damage occur in high voltage installations and electrical equipment in the substations. Seismic loading factor should be considered while designing of electrical equipment to prevent disturbance in power supply during the critical time of rescue operation. Hence equipment and their structures for power generating stations, transmission installations and substations located in seismically active areas shall be designed to function during earthquakes. Procedures for qualifying the seismic design of equipment include analysis by finite element method and shake table testing.

Engineering design of electrical equipment and their supporting structures due to earthquake is a unique and complex problem. The loading caused due to an intense earthquake is abnormal to which most engineering structures might possibly be subjected. However statistically speaking, the probability that any given structure will be affected by the major earthquake is very low. Therefore, the critical equipment and structures shall be designed to withstand high level of earthquake and non-critical equipment to moderate level of earthquake. The evaluation of the seismic reliability of electrical equipment is a very complex due to the non-deterministic properties of the seismic loading. Basics of seismic qualification of electrical equipment, procedure of qualification and relevant codal provisions are presented in this paper.

2. Importance of Seismic Qualification

India is divided into Zone 2, Zone 3, and Zone 5 seismic zones based on evaluation of earthquake potential of the region considering local geology, seismology and other

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specific subsurface characteristics. Areas in Zone 2 will experience lowest level of earthquake vibration and Zone 5 will have highest level of earthquake. Seismic zone map of India as per IS 1893 Part 1 ("IS 1893-Part 1: 2016- Criteria for Earthquake Resistant Design of Structures", 2016) is shown in Figure 1.

Earthquakes produce three-dimensional simultaneous random ground motions. The ground motion is typically broadband random and produces potentially damaging effects over a frequency range of 1 Hz to the cutoff frequency of the response spectra. The cutoff frequency is generally between 32 Hz and 50 Hz. Maximum energy is generally between 1 to 12 Hz frequency ranges.

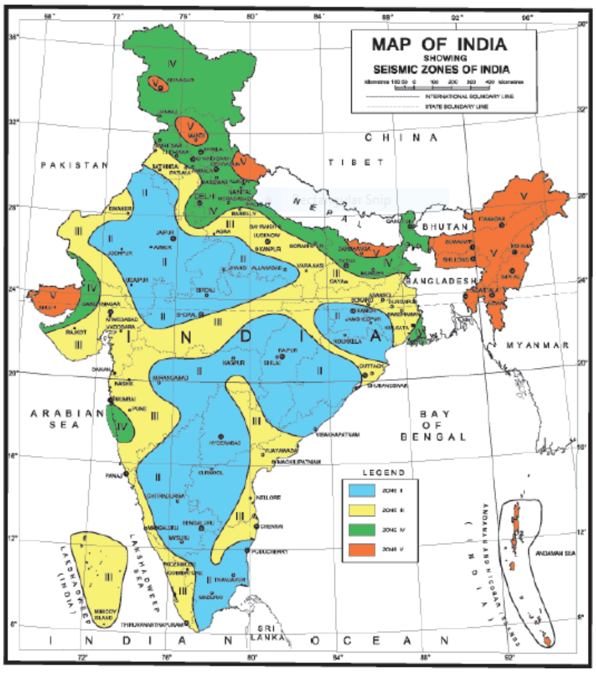

Figure 1. Seismic Zone Map of India

Electrical functional requirement and safety aspect plays major role in determining the geometry of high voltage substation equipment. High voltage substation equipment are tall and slender structure. Substation equipment is mounted on support structure to have minimum ground clearance for safe working. Height of equipment and support structure increases with increase in voltage rating. Natural frequency of 220 kV and above voltage rating substation equipment mounted on support structure is generally below 5 Hz. This falls in the high energy band of earthquake motion, resulting in resonance and amplification of input excitation. Natural frequency of substation equipment falling in high energy band of earthquake motion is the major cause for failure of high voltage substation equipment. Ceramic insulator used in substation equipment is highly brittle and are vulnerable to seismic event. Seismic performances of composite insulators are comparatively better.

Earthquake ground motion with zero period acceleration of 0.1 g can cause massive damage to high voltage substation equipment. Failure may be structural failure which subsequently results in functional failure or functional failure only. Failure of high voltage substation equipment will result in fire, which further escalates the damage and safety of personal is under threat. As per seismic zone map of India, Zone 3, Zone 4 and Zone 5 region can experience 0.1 g or higher ground motion in the event of earthquake.

High voltage substations located in Zone 3, Zone 4 and Zone 5 are under risk of failure. Hence substations with voltage rating of 220 kV and above located in Zone 3, Zone 4 and Zone 5 shall be designed for seismic loading based on substation location to avoid failure. Seismic reliability of substation will avoid failure; ensure uninterrupted power supply during crucial rescues operation and safety of personal are protected.

In case of metal enclosed switchgear and other low voltage equipment, major structural failure are rarely noticed, here functional failure / malfunctioning of equipment during and after seismic event is the challenging factor. Electrical equipment have moving contacts which are held in their position by spring mechanism, malfunctioning of this spring mechanism due to seismic force will result in interruption of power supply. Dynamic force due to seismic event should be considered at design stage.

In case of critical facilities like Nuclear power plant, hospitals, national security systems etc., seismic qualification is highly essential irrespective of voltage rating and type of equipment.

3. Seismic Qualification Approach

3.1. Qualification Approach

The seismic qualification of equipment shall illustrate its ability to perform the function when it is subjected to seismic forces. Following are the most widely used methods for seismic qualification are:

- Predicting the performance of equipment by analysis
- Testing the equipment under simulated seismic load
- Qualifying complicated equipment by integration of test and analysis
- Qualifying the equipment using data from past earthquakes

For selecting the suitable method to verify the seismic performance of the equipment, feasibility of that method for size, type, shape and complexity of the equipment configuration needs to be studied. Electrical equipment have moving parts with different mounting configuration, hence are complex in nature. Evaluation of functional capability is also required in electrical equipment. Seismic qualification by analysis is not recommended for complex equipment that cannot be modeled correctly in the software to predict its response. Seismic qualification by analysis is accepted when it is not possible to perform shake table test due to limitations of the test system.

3.2. Shake Table Test

The shake table test is the realistic method of seismic qualification. The equipment under test is mounted to a moving platform, "shake table" where a three dimensional motion representing any recorded past seismic event or an artificial time history given in standard is applied. The test carried out on a shake table is dynamically similar to a real seismic event, hence it is advantageous compared to analysis.

Earthquakes generate a multi-axial random ground motions. These waves are simultaneous in nature but statistically independent in horizontal and vertical direction. However, while carrying test, single-axis, bi-axial or tri-axial tests are allowed based on end use of the equipment. If single-axis or bi-axial tests are carried out for simulating three-dimensional motion, they should be applied to the table in conservative way for accounting the absence of input signal in other orthogonal direction. If test is carried out in single or bi-axial direction, then the tests shall be done by mounting the specimen along different axes. This results in failure of specimen due to fatigue.

Among various methods recommended in the relevant codal provisions, tri-axial test by shake table method is the most relevant since this will create earthquake random motions simultaneously in all three directions. Frequency content of earthquake random vibration is less than 33 Hz with high energy content at low frequency. Hence long stroke shake table is required for earthquake vibration simulation.

4. Codal Recommendations

The International Building Code (IBC), Bureau of Indian Standard (BIS) and various other standards specific to the topography of different countries en-list the seismic qualification requirements for electrical power system. Seismic qualification level can be selected after studying the level/magnitude of earthquake expected in the region where the substation is located, criticality of the substation and, reliability and safety considerations of the system.

Generalized earthquake test procedure with various levels of qualification in the form of Response spectrum are provided in electrical standards. The level is selected based on location and topography of installation of equipment (high level, moderate level and low level).

IS 1893, Part 1 provides the seismic zone map of India. As per this standard, India is divided in to four seismic zones, zone II, III, IV and V. Zone V being the highest level.

4.1. Nuclear Power Plant

Nuclear power plant being highly critical facility, equipment managing radioactive metal, nuclear waste and equipment responsible for maintaining nuclear power plant in safe shutdown condition should function normally during and after earthquake. Seismic qualifications of this equipment are mandatory and seismic qualification of nuclear power plant equipment is carried out as per IEC/IEEE 60980-344 standard ("IEC/IEEE 60980-344:2020 Nuclear facilities – Equipment important to safety – Seismic qualification", 2020).

Being critical facility, seismic qualification is carried out based on site specific and floor specific earthquake levels. Equipment are subjected to reasonably expected earthquake during operating life of the plant (Operating basis earthquake) and maximum earthquake (Safe shutdown earthquake). Equipment should maintain its functionality and structural integrity during seismic qualification.

4.2. Substation Equipment

"IEC TR 62271-300:2006- Seismic qualification of alternating current circuit breakers" (2006) applicable to circuit breakers mounted on support structure. Generalized required response spectrum RRS for qualification level, high (5 m/s2), and moderate (3 m/s2) and low (2 m/s2) are recommended as per the standard guidelines.

Functional capability of circuit breakers before and after seismic test is also recommended in the standard, as per which functional test needs to be performed for completing the qualification procedure.

HT switchgear is seismically qualified by testing as per "IEC 60068-2-6:2007 Environmental testing - Part 2-6: Tests - Test Fc: Vibration (sinusoidal)" (2007) . This standard provides three qualification levels, AG 2.5 (peak ground acceleration : 0.25 g), AG 5 (peak ground acceleration : 0.5 g) and AG 10 (peak ground acceleration :1.0 g).

"IEEE Std 693-2018 IEEE Recommended Practice for Seismic Design of Substations" (2018) provides procedure of qualification, seismic levels and equipment specific acceptance criteria. "IEEE Std 693-2018 IEEE Recommended Practice for Seismic Design of Substations" (2018) states seismic test methods and functional test requirements for substation equipment. Generalized frequency response spectrum for two qualification levels, high level (1 g) and moderate level (0.5 g) are given in the standard.

5. Tri-Axial Shaker System

The tri-axial shaker system with six degrees of freedom can perform a diverse range of seismic tests on electrical equipment, models of civil engineering structures and other components. The tri-axial shaker system is shown in Figure 2, consist of shaking-table that can simulate true earthquake ground motions simultaneously in all axes without any distortion. More than five hundred seismic qualification tests have been carried out on electrical equipment and supporting structures. Test specimen up to 10,000 kg can be mounted for qualification using this system. The shake table can move in three axes with six degrees of freedom. Time history of any past recorded earthquake can also be simulated using this system.

Figure 2. Tri-axial Shaker System

5.1. Simulating the Earthquake

The goal of seismic simulation is to reproduce the postulated earthquake environment in a realistic manner. Time history generation is the most effective while defining the ground accelerations during an earthquake. Shake table test are carried out by subjecting the specimen/equipment to three dimensional vibration that conservatively simulates an earthquake of a specific intensity on the test bed. If the specimen/equipment performs its function after surviving this earthquake vibration, it is considered seismically qualified.

Selection of earthquake environment is the first step in seismic qualification process. The factors which are considered while simulation is mounting location, equipment type, expected earthquakes in the region etc. Site specific, floor specific and direction specific earthquake environment are used for seismic qualification of highly critical installation like Nuclear power plant equipment. Seismic qualification of substation equipment is generally carried out using generalized Required Response Spectrum (RRS). The shape of the Required Response Spectrum is a broadband response spectrum to account for the effects of earthquakes in different area and considering site conditions ranging from rock to soft soil.

5.2. Mounting of Test Specimen

The equipment under test is mounted on the tri-axial shake table in such a manner that it simulates the actual service condition of site. The mounting method shall be the same as recommended in-service and shall provide correct bolt-size, torque, configuration, weld patten etc. The effect of electrical connections, conduit, sensing lines, and any other interfaces shall be considered. Substation equipment is seismically qualified along with supporting structure. Seismic qualification report is specific to the mounting condition indicated in the test report, change of mounting condition in the field invalidate the test report.

5.3. Preliminary Dynamic Test

Though exploratory vibration tests are generally not part of the seismic qualification requirements, but are carried out on equipment to determine the dynamic characteristics of the equipment. These low input level vibration tests are normally described as resonance search test. This test is carried out by sine sweep method with constant table acceleration. The response of equipment is measured to calculate resonance frequency and damping. This test is performed by subjecting table to slow sinusoidal sweep vibration with the input in uni-axial direction individually. Resonance search test is again repeated after seismic test to evaluate structural integrity of the specimen after seismic vibrations.

5.4. Seismic Test using Shake Table

Seismic test was carried out as per relevant standard for known value of zero period acceleration level. Statistically independent spectrum compatible time histories were generated for two horizontal and vertical directions corresponding to damping calculated after resonance search test. Time history test was carried out by simultaneous three-dimensional random vibration. Typical Required Response Spectrum (RRS) and Test Response Spectrum (TRS) are shown in Figure 3. During time history test, sample is kept in energized condition and vibrational and functional monitoring is carried out.

6. Monitoring

6.1. Functionl Monitoring

Functional capability of equipment is checked before, during and after seismic vibration simulation. Functional tests before and after seismic qualification is generally carried out as per the product specific standard. Functional evaluation during seismic test is decided based on functional requirement, like incase of switchgear panel condition of

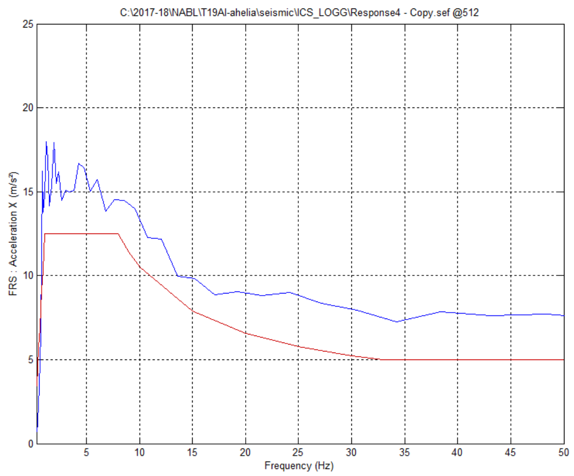

Figure 3. TRS and RRS

breaker and relays are monitored for change in status during seismic qualification.

6.2. Vibration Response Monitoring

Acceleration experienced on the equipment due to seismic vibration is measured by mounting accelerometers at critical locations. Strain developed due to earthquake motion is also measured by mounting strain gauge to compute stress. Stress developed should be less than yield strength.

7. Acceptance Criteria

Acceptance criteria are as follows:
a) Ability to perform its functions during and/or after the time it is subjected to the force resulting from earthquake vibration

- The dielectric strength, switching capability and current carrying capability should not be impaired
- No change in status or chattering of relay / breaker contacts
- Operation of device during seismic test, if required.

b) No permanent deformation, dislocation, breakage or cracks.

8. Conclusion

Earthquake is a natural phenomenon where the time of occurrence cannot be predicted. The destruction caused by earthquake vibration to human, wildlife and infrastructures is indescribable. It's a natural disaster which causes huge damage to power system, substation equipment and civil structures. However, for a reliable and safe power system and substation during an earthquake, consideration to seismic dynamic loading has be given in the initial design phase as one of the design parameter in addition to their basic performance parameters. This can be done by seismic qualification of equipment and supporting structures by actual testing by shake table method. If seismically qualified equipment is installed in the substations, loss to human life and equipment during earthquake can be minimized. It will also ensure safe power supply during critical time of rescue operations post-earthquake. Hence, to provide safe power supply without interruptions during and after earthquake, seismic qualification of equipment is recommended. The seismic loads calculated during seismic test shall be taken into design calculations with other service loads and total withstand capability of the equipment can be evaluated.

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