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Seismic Performance of High Voltage Composite Insulator Circuit Breaker

R. Panneer Selvam* and Yamini Gupta

Central Power Research Institute, Bengaluru – 560080, Karnataka, India; selvam@cpri.in, yaminigupta@cpri.in

Abstract

Dynamic seismic force causes damage to electrical equipment and structures resulting in loss of human and animal life. High voltage substation equipment are highly vulnerable to earthquake event compared to low voltage distribution network. Vulnerability to seismic event increases with increase in voltage rating of substation due to taller and slender porcelain structures. Porcelain insulators used in substation equipment have high compressive strength but weak tensile strength. Hence ceramic insulators are the weakest part in the substation equipment in the event of earthquake. Earthquake with 0.1g zero period acceleration can cause massive damage to high voltage substation equipment. Substation equipment with composite insulator are comparatively less vulnerable to seismic loading. Central Power Research Institute (CPRI) is equipped with state-of-the-art tri-axial shake table facility for simulating tri-axial earthquake vibration. Seismic qualification methods, codal provisions and seismic performance of 145 kV three pole operated composite insulator SF6 circuit breaker by shake table method are discussed in this paper. The seismic strain at critical locations, response acceleration on circuit breaker are presented along with relative displacement at the terminal of circuit breaker.

Keywords: Damping, Natural Frequency, Seismic Qualification, Substation Equipment, 145kV SF6 Circuit Breaker

1. Introduction

An earthquake is the sudden shaking of the surface of the Earth caused by movement of the Earth's crust. Earthquake causes massive damage to buildings, industrial structures and equipment, causing loss of life. Vibration caused due to earthquakes are three-dimensional random in nature. The earthquake ground motion are amplified or attenuated by structures depending on the system's natural frequencies and damping. Performance of equipment under seismic event can be evaluated by simulating postulate tri-axial random vibration using shake table. Magnitude of excitation for seismic qualification is arrived by considering geographical region, local site, soil conditions, historical seismic data, degree of conservatism and dynamic properties of mounting structures. Earthquake vibration levels used for checking performance of equipment can be of site specific or generalised response spectrum mentioned in National and International standards. Though post-earthquake reconnaissance has identified high voltage substation equipment being particularly vulnerable to earthquake shaking, not much attention is given in our country in preventing such damages. Designing of equipment for seismic loading can prevent disruption in power supply for many days during the critical phase of rescue operation. Reliability of electrical equipment and their supporting structures against earthquake hazards has become prime importance.

The satisfactory operation of a substation during and after an earthquake depends on the survival, without malfunctioning, of many diverse type of equipment. Anchorage and interconnections of each equipment should be engineered to avoid failure of substation equipment. Porcelain insulators used in substation equipment are highly brittle in nature and more likely to fail in the event of earthquake. High voltage substation equipment are taller and slender porcelain structure having lower natural frequencies and is more susceptible to earthquake loading. Substation equipment with composite insulator are comparatively less vulnerable to seismic loading.

Design and testing of electrical equipment and structures for seismic loading becomes very important for the

**Author for correspondence*

substations located at active seismic zone. This will ensure reliable, uninterrupted and safe power supply. In the case of critical facilities like Nuclear power generating station, hospitals etc., it is mandatory to design electrical equipment and structures for seismic loading and validate the design by testing including verification of functioning of equipment based on requirement.

In order to meet the basic requirements regarding seismic qualification of equipment and thereby to ensure reliable power transmission, Earthquake Engineering Laboratory capable of performing a diverse range of seismic qualification requirements on equipment, sub-assemblies and components as per National and International standards has been established at CPRI, Bengaluru. Seismic qualification of electrical equipment like transformers, instrument transformers, isolators, circuit breakers, switchgears, electrical panels, battery banks, UPS etc., are being carried out using this facility. Seismic qualification methods, codal provisions and seismic performance of 145 kV three pole operated composite insulator SF6 Circuit Breaker (CB) by shake table method are discussed in this paper. The seismic strain and response acceleration on circuit breaker are presented along with relative displacement at the terminal of circuit breaker.

2. Seismic Qualification

The seismic qualification of equipment should demonstrate equipment's ability to perform its function during and after the time it is subjected to the dynamic forces resulting from earthquakes.

2.1 Seismic Qualification Methods

The most commonly used methods for seismic qualification are grouped into four general categories that is;

- Predict the equipment's performance by analysis
- Test the equipment under simulated seismic conditions
- Qualify the equipment by a combination of test and analysis
- Qualify the equipment through the use of experience data

Each of the preceding methods or other justifiable methods may be adequate. The choice of selection of method to verify the ability of the equipment to meet the seismic qualification requirements is generally based on the practicality of the method for the type, size, shape and complexity of the equipment configuration.

Electrical equipment being complex in nature, it is difficult to model and predict the equipment performance by finite element analysis precisely. Also by finite element analysis method, only the physical conditions like deflection and stress due to seismic loading in the equipment can be evaluated. However, functioning of electrical equipment during and after seismic event can be checked only by shake table testing. Hence analysis method of seismic qualification is not recommended for electrical equipment. Analysis method is acceptable only if it is not possible to conduct shake table testing due to limitation of the test system.

2.2 Tri-axial Shake Table Facility at CPRI

Seismic qualification by shake table test is more realistic method of earthquake testing. The shake table test is reliable validation test to assess the seismic performance of structures and equipment. Specimens of interest are mounted on the table and tests are carried out simulating postulated earthquakes. In addition to mechanical integrity checking, functioning of equipment can also be checked while performing earthquake qualification by shake table method.

The tri-axial shaker system with six degrees of freedom is capable of performing a diverse range of seismic qualification test on equipment, sub-assemblies and components as per National / International standards. The shake table is of size 3 m x 3 m and test specimen weighing up to 10000 Kg can be seismically qualified. Simultaneous three dimensional random earthquake vibration can be simulated using this system. Real time earthquake can also be simulated based on digital values of real time earthquake time histories. Frequency range of test facility is 0.1 to 50 Hz and maximum velocity of 1.0 m/s can be achieved. The advanced control system allows the reproduction of earthquake ground motions with high fidelity and little distortion. The seismic qualification tests on various electrical equipment are being conducted using the Tri-axial earthquake simulation system.

2.3 Codel Recommendations

Seismic performance of electrical equipment is generally carried out using generalised response spectrum. The response spectrum provides information about maximum response of single degree of freedom oscillators as a function of oscillator frequency and damping when subjected to an input earthquake motion. Seismic qualification levels of, High level (0.5g) and moderate level (0.25g / 0.3g) response spectrum are mentioned in most of electrical standards. Based on substation location, required levels can be selected for seismic qualification. Earthquake excitation levels can also be obtained from The International Building Code (IBC), Bureau of Indian Standard (BIS) and various country specific seismic standards. Site specific response spectrum are used to study performance of critical facility like Nuclear power generating station.

The IEEE Standard 693, "Recommended Practice for Seismic Design of Substations" clearly defines seismic qualification levels, qualification procedures, and acceptance criteria. IEEE Std 693 is equipment specific, stating the seismic qualification procedure and functional check requirements for each type of equipment specifically. Generalized frequency response spectrum for two qualification levels, high qualification level (0.5 g) and moderate qualification level (0.25 g) are recommended in this standard.

The IEC TR 62271 – 300, "Seismic qualification of alternating current circuit breakers", applies to circuit breaker with support structures and does not cover seismic qualification of metal enclosed switchgear. Generalised frequency response spectrum for three qualification level, high qualification level (5 m/s^2), moderate qualification level (3 m/s^2) and low qualification level (2 m/s^2) are recommended in this standard.

Functional requirement of circuit breakers before and after seismic qualification test are defined in this standard.

3. Seismic Qualification of 145 kV SF6 Circuit Breaker

Seismic performance of 145 kV three pole operated composite insulator SF6 circuit breaker by shake table method was evaluated as per IEC TR 62271-300 for high severity level with 0.5g zero period acceleration level. Basic functional performance of circuit breaker was evaluated before and after seismic qualification. In addition to this, response acceleration and strain values are recorded at critical locations. Details of 145 kV SF6 Outdoor circuit breaker are as follows:

a. Rated voltage – 145 kV
b. Number of Poles – Three
c. Number of interrupter unit per pole – One
d. Spring operating mechanism (one number)
e. Control system
f. Common base frame (support structure)
g. Overall height - 6274 mm
h. Weight including structure - 1200 Kg
i. Composite insulator

3.1 Mounting

The equipment to be qualified should be mounted on the seismic vibration table in a manner that simulates the intended service mounting. The mounting method is same as that recommended for actual service, and the recommended bolt size, torque, configuration and weld pattern and type are used. For example, substation equipment, current transformer is mounted on support structure of actual dimension and configuration while testing. If equipment is mounted with variety of support and parameters of support are not known then equipment is qualified with elevation factor. Super elevation factor varies from 1.5 to 2, based on standards.

145 kV SF6 Outdoor circuit breaker was mounted on common base frame and fixed to tri-axial shake table. Photograph of Circuit breaker mounted on shake table is shown in Figure 1. Accelerometers were mounted on circuit breaker to measure response during seismic vibration simulation. Accelerometers were mounted at the top of specimen near the top terminal plate, on common base frame and on control assembly. Strain gauges were mounted to measured strain induced during tri-axial earthquake vibration. Strain values measured at critical location can be used to determine the combined stress by adding other service loads, like internal pressure, static terminal load etc. Based on combined stress the total withstand capacity of circuit breaker can be evaluated. Relative displacement is also measured near top terminal plate of circuit breaker; this data can be used to design interconnections.

3.2 Vibration Response Investigation

Vibration response investigation is performed to determine the dynamic characteristics of the equipment. The vibration response investigation is performed with a low

Figure 1. 145 kV SF6 circuit breaker mounted on shake table.

level sinusoidal vibration. Sinusoidal sweep is performed for the frequency range of interest with constant excitation level with input in uni-axis.

During sinusoidal sweep, input excitation to the table and response on the specimen are measured. Transfer function of response to input excitation is computed in frequency domain and vibration response characteristic of specimen, resonance frequencies and damping are obtained. Frequency range of interest for vibration response investigation during seismic performance evaluation is 0.1 to 35 Hz and low level of excitation required to excite the specimen (0.075g) is used.

Resonance frequencies found are shown in Table 1. Resonance frequency plot at the top of specimen near terminal plate (Y-phase) in transverse direction is shown in Figure 2 and on common base frame in transverse direction is shown in Figure 3. First resonance frequency is very close in both longitudinal and transverse direction. Vertical direction being very rigid has no resonance up to 35 Hz. From Figures 2 and 3 it is very clear that at resonance frequency of 2.13 Hz, acceleration amplification at the top of circuit breaker is nearly four times compared to common base frame. Also acceleration amplification at common base frame is nearly ten times at resonance frequency of 2.13 Hz and fourteen times at resonance frequency of 7.32 Hz with respect to table excitation.

Acceleration amplification on top of support structure is very high at resonance frequency. However, most of standards specify option of qualifying substation equipment without support structure with super elevation factor of 2 to 2.5, which is less when compared with experimental data. Further study is required in this area.

Damping is evaluated by half power method; lowest value of damping evaluated is 2.92%. Damping value evaluated by Vibration response investigation is an input data for seismic test. Also resonance frequencies, damping and amplification values obtained during vibration response investigation can be used for failure analysis and future design optimization.

Table 1. Resonance frequencies

Location	Direction	Resonance frequency, Hz
Top of CB near terminal plate (Y-Phase, centre pole)	Longitudinal	2.08 & 5.49
	Transverse	2.13 & 7.32
	Vertical	No resonance
Top of CB near terminal plate (B-phase, side pole)	Longitudinal	2.08 & 5.49
	Transverse	2.13, 7.32 & 9.03
Common base frame	Transverse	2.13, 7.32 & 9.03
	Vertical	No resonance
Control assembly	Longitudinal	2.08 & 5.49
	Transverse	2.13, 7.32 & 9.03
	Vertical	No resonance

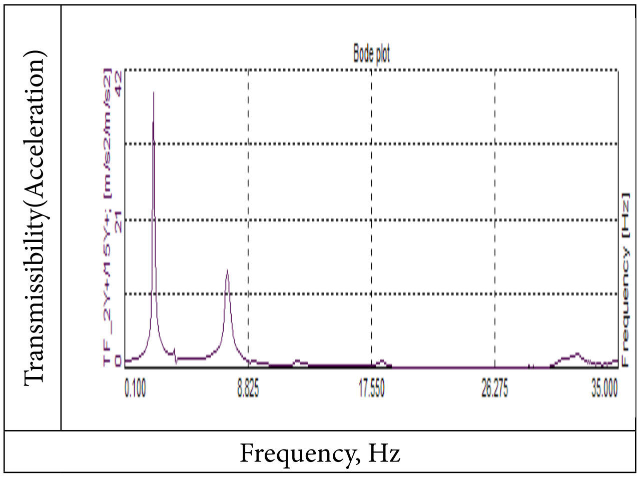

Figure 2. Resonance frequency (top of CB, Y-phase, transverse direction).

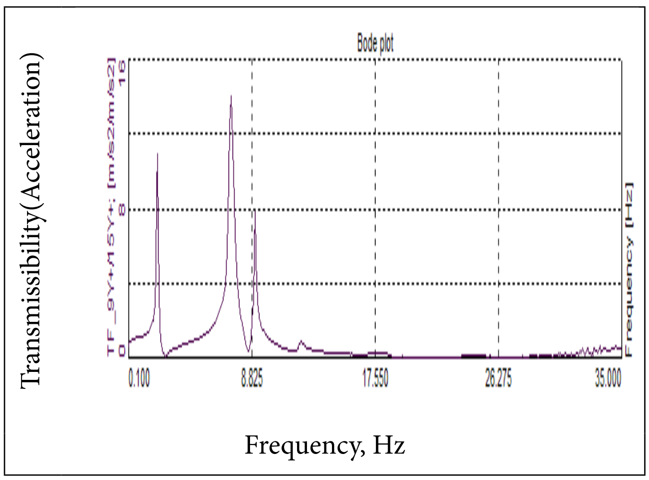

Figure 3. Resonance frequency (common base, transverse direction).

3.3 Multi-frequency Time History Test

Multi-frequency time history test is carried out by vibrating shake table with statistically independent tri-axial time histories. Time histories are generated to produce a Test Response Spectrum (TRS) that closely envelops the Required Response Spectrum (RRS) over the frequency range of interest (1 to 35 Hz) for qualification level AF5, 5 m/s^2 zero period acceleration. Response spectrum in vertical axis is with acceleration level of 50% of that in the horizontal axes. Damping value calculated from vibration response investigation can be used as input. In case damping value is not known, 2% damping is recommended for substation equipment and 5% for electrical panels.

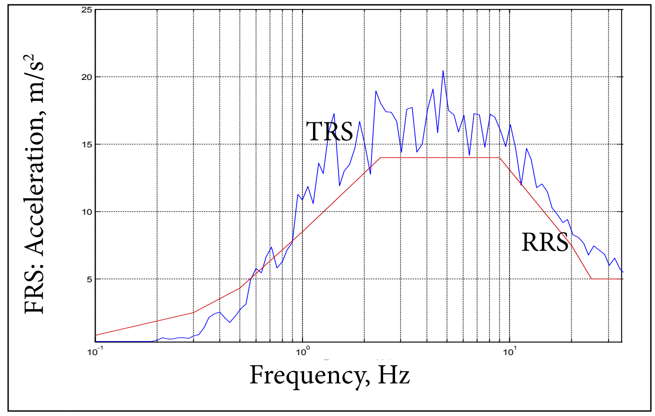

Figure 4. RRS and TRS

Lowest damping value evaluated using vibration response investigation by half power method is 2.92%, spectrum compatible time histories are computed with conservative value of 2% damping for testing. RRS and TRS for horizontal axis is shown in Figure 4. TRS envelops RRS for the frequency range of 1 to 35 Hz as per standard requirement.

During multi-frequency time history test, responses of the equipment in terms of acceleration, strain and relative displacement were recorded at critical locations.

Time history of input table acceleration, acceleration at common base frame and at the top of circuit breaker is shown in Figures 5–7. Based on acceleration time history, it is clear that the acceleration is amplified almost 3.4 times at the common base frame and 7 times at the top of circuit breaker in time domain with reference to table excitation.

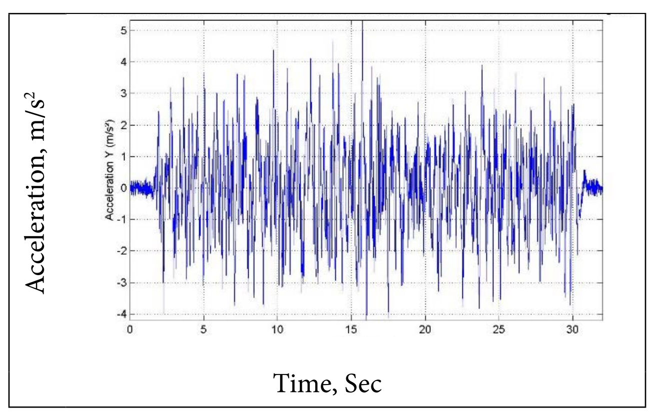

Figure 5. Table acceleration. Peak value: +5.34 and -4.20.

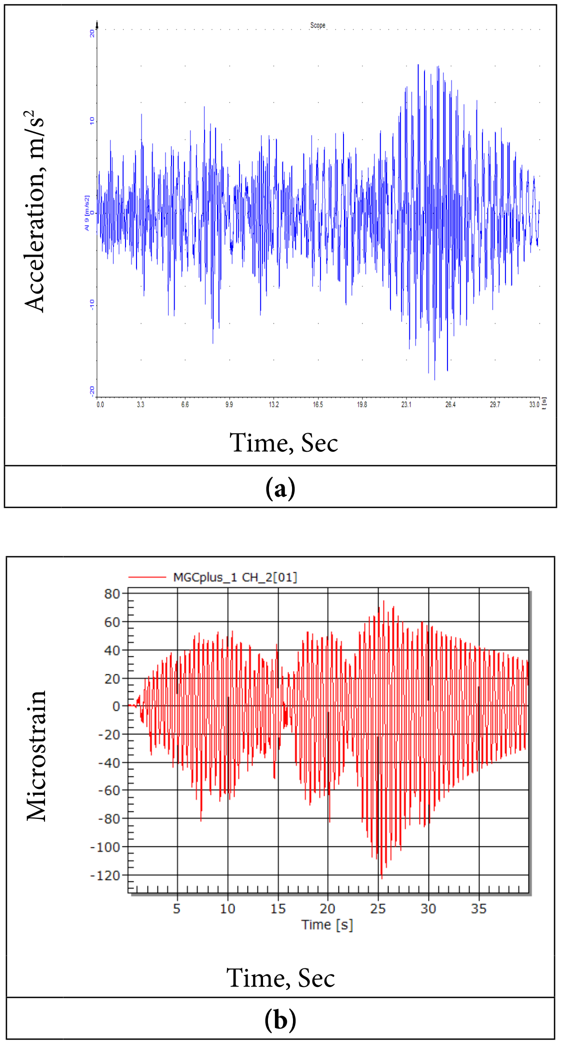

Figure 6. **(a)** Acceleration at common base frame Peak value: +16.28 and -18.10. **(b)** Time history of strain at bottom of composite insulator on metal end fitting, Peak value = +74.72 and -122.83 microstrain.

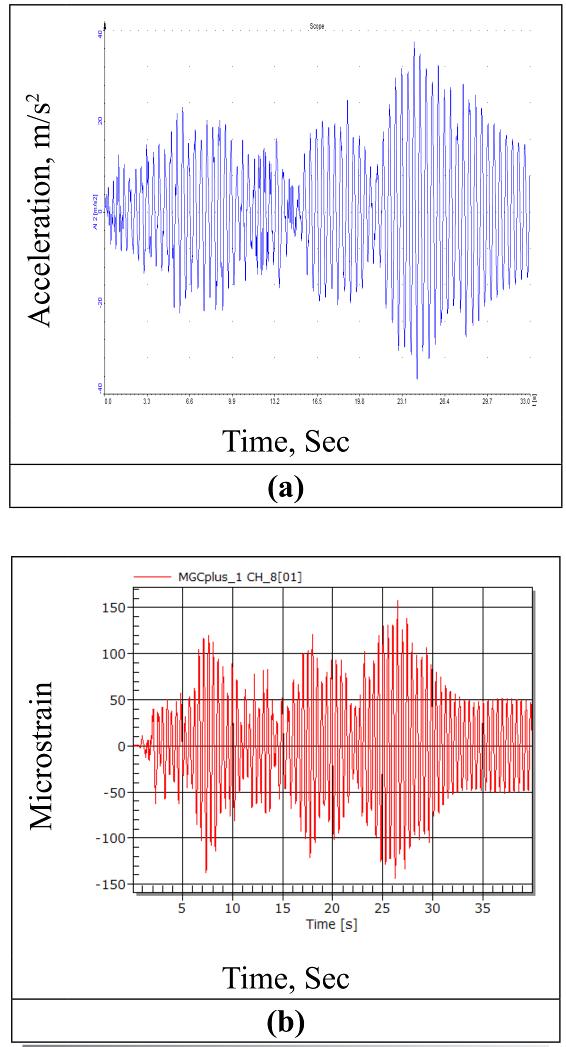

Figure 7. (a) Acceleration at top of circuit breaker. Peak value: +37.44 and -36.84. (b) Time history of strain at the base of support structure, Peak value = +157.45 and -143.47 microstrain.

Strain induced during seismic time history test at the bottom of composite insulator on metal end fitting and at the base of support structure in transverse direction is as shown in Figures 6 and 7.

The seismic stresses determined by test should be added algebraically with other service loads to determine the total withstand capability of the circuit-breaker. Relative displacement measured during seismic test was 81.2 mm, this will be input data for design of interconnection in the substation.

3.4 Functional Checks

Functioning of circuit breaker and no-load opening and closing time were checked before and after seismic qualification. Opening and closing of circuit being the basic requirement of circuit breaker, no-load time measurement ensures breaker capability of withstanding seismic load. No-load opening and closing time measurement results before and after seismic test are shown in Table 2.

Table 2. No-load time measurement

No-load opening time measurement			
% of rated control supply voltage	Time, milli seconds		
	Phase	Pre-seismic	Post-seismic
110%	R	27.50	27.50
	Y	27.20	27.20
	B	27.30	27.20
100%	R	28.90	28.60
	Y	28.70	28.30
	B	28.70	28.30
70%	R	35.60	35.00
	Y	35.30	34.60
	B	35.40	34.70
No-load closing time measurement			
% of rated control supply voltage	Time, milli seconds		
	Phase	Pre-seismic	Post-seismic
110%	R	57.60	59.30
	Y	57.70	59.40
	B	57.80	59.60
100%	R	59.50	57.10
	Y	59.80	57.30
	B	59.90	57.60
85%	R	62.20	61.10
	Y	62.30	61.40
	B	62.40	61.70

4. Performance Evaluation

Seismic performance of circuit breaker is evaluated based on mechanical integrity and basic functional verification.

Mechanical Integrity: Observations made with respect to mechanical integrity of circuit breaker are, no physical damage and no permanent deformation. Based on strain data obtained during seismic qualification, stress value can be evaluated.

Functional Verification: Operating condition of circuit breaker, functioning of auxiliary and control circuits, change in status of circuit breaker during earthquake vibration and No-load opening and closing time measurement are checked to evaluate functioning of circuit breaker.

Circuit breaker meets all the acceptance criteria as per IEC standard and is seismically qualified

5. Conclusions

High voltage substation equipment are highly vulnerable to seismic event. Based on past experience it clear that earthquake with 0.1g zero period acceleration can cause massive damage to substation equipment. The reliability and safety of electrical power systems after an earthquake can be ensured by considering seismic dynamic loading as one of the design parameter in addition to basic electrical performance parameters. High voltage substation equipment with composite insulators are less susceptible to earthquake loading in comparison to highly brittle porcelain equipment. It is only through seismic qualification of equipment and supporting structures, loss to human life and equipment can be minimized. This will ensure uninterrupted, safe power supply during crucial post-earthquake rescue operation. The seismic stresses determined by test should be taken into design consideration with other service loads to determine the total withstand capability of the circuit-breaker. Relative displacement measured during seismic qualification will be input data for design of interconnection in the substation. Power utilities may utilize the state-of-the-art facilities available at CPRI to ensure reliability and safety of electrical power systems.

6. Acknowledgement

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7. References

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