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Evaluation of Seismic Behaviour of High Voltage Switchgear Panel by Shake Table Testing

R. Panneer Selvam*, Yamini Gupta and D. Nagesh Babu

Central Power Research Institute, Bengaluru – 560010, Karnataka, India; selvam@cpri.in, yaminigupta@cpri.in, nageshbabu @cpri.in

Abstract

Switchgear and controlgear plays a vital role in electrical power distribution system. Switchgear and controlgear are designed for electrical performance requirements including short circuit, temperature and humidity environmental conditions. But design aspects due to a seismic event are usually not taken into consideration. Earthquake shock waves causes vigorous ground shaking which are three dimensional in nature. Past-earthquake records have revealed that electrical equipment are vulnerable to seismic event, this lead to an increased focus on the earthquake performance evaluation of electrical equipment. Dynamic loading due to earthquake should be considered at the design stage in addition to other performance parameters. Designing switchgear for earthquake loading and validating design by testing can ensure uninterrupted and safe power supply during crucial time of post-earthquake rescue operations. In case of metal enclosed switchgear, functioning of equipment during and after seismic event is the major concern. Malfunctioning due to breaking or loosening or deformation of components, loss of output due to open circuit or short circuit and spurious operation of protective relays are observed during past seismic events. Central Power Research Institute (CPRI) is equipped with state-of-the-art tri-axial shake table facility for simulating true earthquake vibration. Seismic performance evaluation of high voltage switchgear by shake table method is presented in this paper.

Keywords: Damping, H V Switchgear and Controlgear, Natural Frequency, Seismic Qualification

1. Introduction

Vibration caused due to earthquakes is complex multi frequency in nature having two horizontal and one vertical component. Shock waves due to earthquake cause massive damage to equipment and structures, resulting in loss of human and animal life. Electrical equipment are vulnerable to earthquakes, high voltage substation equipment are highly susceptible. However, not much importance is given in our country in preventing such damage. Uninterrupted electrical power supply is the most important requirement for carrying out any type of rescue operations post-earthquake. Dynamic loading due to seismic event should be considered while designing electrical equipment. Seismic loading shall be calculated based on mounting location of equipment.

Frequency content of earthquake vibration is usually less than 33 Hz, with maximum energy in low frequency range. Hence shake table used for seismic qualification shall be capable of simulating low frequency vibration. Servo hydraulic shaker system with long stroke which can simulate vibration even from 0.1 Hz frequency are used for seismic qualification. In addition to low frequency vibration, tri-axial vibration simulation is required for realistic replication of earthquake conditions. Electro dynamic shaker system can simulate vibration from 5 Hz onwards and are not suitable for seismic qualification test. The seismic qualification shall demonstrate the ability of equipment to withstand seismic stress and perform its function during and after seismic event. Seismic qualification can be carried out by finite element analysis, actual testing under simulated seismic conditions and combination of analysis and testing. In case of electrical equipment functional evaluation during and after seismic event is the major criterion for seismic qualification in addition to stress analysis. This can be carried out only by shake table method of seismic qualification. Precise modelling of complex electrical equipment and predicting

*Author for correspondence

the performance by finite element analysis method is difficult. In case of shake table limitation with respect to volume of sample and payload capacity, combination of shake table method and analysis can be used with shake table test results being an input for analysis

Earthquake Engineering Laboratory of CPRI is equipped with state-of-the-art tri-axial shake table facility for seismic qualification of equipment. Seismic performance evaluation of high voltage instrument transformer, transformer, transformer bushing, lightning arrestor, isolator, circuit breaker, bus duct, Switchgear and controlgear etc. are being carried out as per National and International standards. Evaluation of seismic behaviour of 12 kV metal enclosed AC switchgear panel by shake table method is presented in this paper.

2. Details of Shake Table

Seismic qualification by shake table method is the most realistic method. The equipment to be qualified is fixed to a moving platform called shaking table to which a motion history representative of past seismic events or artificial time history is applied. Shake table can simulate dynamic conditions similar to real time earthquake event. Simulating earthquake vibration in two horizontal and vertical axes simultaneously (tri-axial vibration) is recommended in most of standards since earthquake produces random motion simultaneously in all three directions.

CPRI tri-axial shake table facility can simulate true earthquake vibration. The shake table is a servo hydraulic system with six degree of freedom. Salient features of tri-axial shaker system are shown in Table 1.

Table 1. Salient features of tri-axial shaker system

Maximum payload	10 tons
Degree of freedom	Six (3 translatory and 3 rotational)
Maximum height of specimen	10 m to 14 m (based on specimen configuration)
Velocity	± 1000 mm/s
Displacement	±150 mm (horizontal) ±100 mm (vertical)
Frequency range	0.1 to 50 Hz

3. Seismic Behaviour of HT Switchgear

Switchgear and controlgear assemblies selected for seismic qualification should reasonably represent the whole system for the purpose of structural and functional checks. Switchgear shall include the switching devices with their relevant operating mechanism and control equipment, and their electrical and mechanical interfaces. Performance of 12 kV metal enclosed AC switchgear panels under seismic environmental condition was evaluated as per IEC/TS 62271-210 "Seismic qualification for metal enclosed and solid-insulation enclosed switchgear and controlgear assemblies for rated voltages above 1 kV and up to and including 52 kV".

Selection of earthquake environment is based on geographical mounting location of equipment and expected earthquakes in the specified location. 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). Generalised response spectrum with 0.5g zero period acceleration (severity level-1) and with 1g zero period acceleration (severity level-2) are recommended in IEC standard. Required response spectrum is broadband and smoothened spectrum. Spectrum corresponding to exact damping commuted based on resonance search test can be used or in case the exact damping behaviour is unknown, 5 % damping ratio is recommended.

Severity Level-1 is recommended for equipment mounted at the ground level and severity Level-2 for equipment mounted at upper floor levels.

3.1 Mounting

Details of 12 kV metal enclosed AC switchgear panels are as follows:

a) 12 kV, 2500A, 50kA/3sec, metal enclosed switchgear panel incorporating withdrawable 12 kV SF6 circuit breaker, current transformer, voltage transformer and earth switch coupled together with 12 kV, 2500A, 50kA/3sec, metal enclosed switchgear panel incorporating withdrawable 12 kV SF6 circuit breaker, current transformer and earth switch.

b) Overall dimension 2275mm X 1878mm X 2730mm and weight 2930 kg.

Photograph of Switchgear mounted on shake table is shown in Figure 1.

The equipment to be tested is mounted on the shake 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 are used. Transducers were mounted on switchgear to measure cubical response during vibration simulation. Accelerometers were mounted at top of cubical, at centre of gravity and at other critical components. Strain gauges were mounted on critical load bearing members.

Figure 1. Switchgear unit mounted on shake table.

3.2 Evaluation of Dynamic Properties

Dynamic behaviour of vibrating bodies depends mainly on natural frequency and damping. Natural frequency and damping of a system can be determined by base excitation method. Sample of interest is mounted on shake table and excited from base with low level. Acceleration response acceleration on the sample and excitation level is data logged. Transmissibility plot of response acceleration to table excitation level illustrates natural frequency of the sample. Damping is computed by half-power method.

Resonance frequencies of switchgear cubical and critical components mounted inside the cubical was found by exciting shaker system with low level sinusoidal vibration, frequency swept from 1 to 35 Hz with constant acceleration of 2 m/s^2 along all the three axes individually. During sinusoidal sweep, table acceleration and response acceleration on the sample are recorded and resonance frequencies are computed. Resonance frequencies and damping before seismic test will give us information about dynamic properties. Evaluation of resonance frequencies after seismic test will indicate the structural integrity of the switchgear cubical. Change in resonance frequencies shall be within 20% as per the recommendations of standard. The Resonance frequencies are shown in Table 2. Typical resonance search test graph is shown in Figure 2.

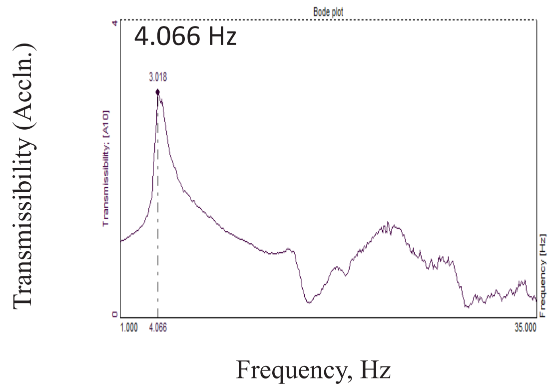

Figure 2. Resonance search test.

Value of damping calculated by half power method from resonance search data was 8.83%.

Table 2. Resonance frequencies

Location	Direction	Resonance Frequency, Hz	
		Before seismic	After seismic
Cubicle	Front-back	12.637	12.825
	Side-side	4.066	4.004
	Vertical	29.716	29.591
VCB	Front-back	11.824	11.574
	Side-side	4.066	4.004
	Vertical	23.085	23.210

3.3 Performance under Multi-frequency Vibration

11kV switchgear was proposed to be mounted at ground level, hence seismic qualification was carried out for 0.5 g zero period acceleration. Required Response Spectrum (RRS) of 0.5 g in horizontal directions, 5% damping was used for testing. Spectral acceleration in vertical direction is 80% of horizontal direction. Statistically independent spectrum compatible artificial time histories were generated for two horizontal and vertical directions. 11 kV switchgear was subjected to multi-frequency time history vibration simultaneously in all three directions. RRS and Test Response Spectrum (TRS) for horizontal axis is shown in Figure 3. Maximum strain induced to due multi-frequency seismic vibration on structural member of cubical is +96.78 and -192.70 micro strain, time history of strain is shown in Figure 4.

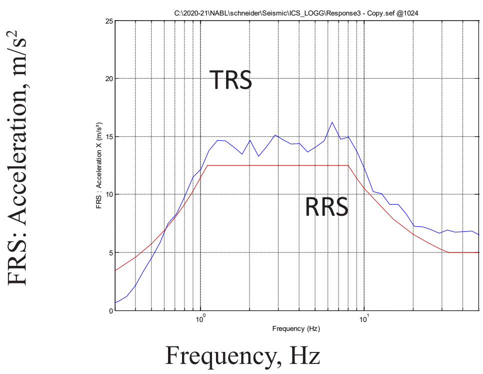

Figure 3. RRS and TRS.

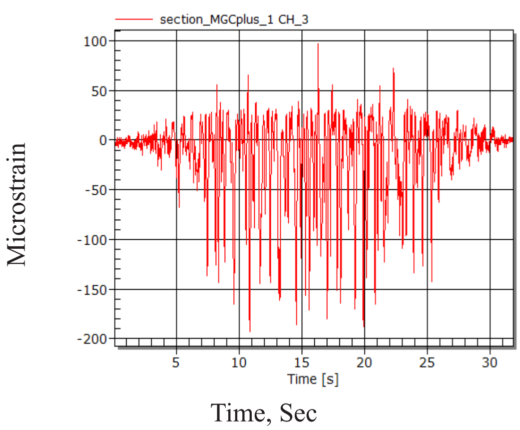

Figure 4. Time history of strain.
Peak value = +96.78 and -192.70 micro strain

3.4 Functional Evaluation

Proper functioning of switchgear was ensured by evaluating following basic functional requirement pre and post seismic qualification:

a) Operation of circuit breaker
b) Closing time of circuit breaker
c) Opening time of circuit breaker
d) Resistance measurement of the main circuit
e) Power frequency withstand voltage test

Functional test results shown in Table 3.

In addition to functional evaluation of switchgear cubical pre and post seismic qualification, functional performance is also checked during seismic loading. During time history test control circuit was energized, vacuum circuit breakers were kept in closed position and not operated. Opening and closing operation of circuit breaker during seismic vibration shall be decided based on field of application. Auxiliary contacts of vacuum circuit breaker were monitored for change in status. Vacuum circuit breakers were in closed position before start of test and no change in status noticed after seismic vibration.

Table 3. Functional evaluation

<table>
<tr><td colspan="7">a) Circuit breaker opening time</td></tr>
<tr><td rowspan="3">Control supply voltage</td><td colspan="6">Opening time, milli second</td></tr>
<tr><td colspan="2">R-phase</td><td colspan="2">Y-phase</td><td colspan="2">B-phase</td></tr>
<tr><td>Pre</td><td>Post</td><td>Pre</td><td>Post</td><td>Pre</td><td>Post</td></tr>
<tr><td>110%</td><td>48.6</td><td>48.7</td><td>48.8</td><td>48.9</td><td>46.6</td><td>46.7</td></tr>
<tr><td>100%</td><td>51.2</td><td>51.3</td><td>51.3</td><td>51.4</td><td>49.5</td><td>49.3</td></tr>
<tr><td>70%</td><td>65.6</td><td>65.2</td><td>65.7</td><td>65.3</td><td>63.5</td><td>63.1</td></tr>
<tr><td colspan="7">b) Circuit breaker closing time</td></tr>
<tr><td rowspan="3">Control supply voltage</td><td colspan="6">Closing time, milli second</td></tr>
<tr><td colspan="2">R-phase</td><td colspan="2">Y-phase</td><td colspan="2">B-phase</td></tr>
<tr><td>Pre</td><td>Post</td><td>Pre</td><td>Post</td><td>Pre</td><td>Post</td></tr>
<tr><td>110%</td><td>62.8</td><td>62.4</td><td>63.2</td><td>62.7</td><td>63.4</td><td>62.8</td></tr>
<tr><td>100%</td><td>68.9</td><td>67.2</td><td>68.3</td><td>67.6</td><td>68.5</td><td>67.7</td></tr>
<tr><td>85%</td><td>84.9</td><td>81.4</td><td>85.2</td><td>81.7</td><td>85.4</td><td>81.9</td></tr>
<tr><td colspan="7">c) Power circuit resistance measurement</td></tr>
<tr><td rowspan="2">Test condition</td><td colspan="6">Resistance, μΩ</td></tr>
<tr><td colspan="2">R-phase</td><td colspan="2">Y-phase</td><td colspan="2">B-phase</td></tr>
<tr><td>Pre-seismic at 23.8 °C</td><td colspan="2">123.90</td><td colspan="2">127.43</td><td colspan="2">117.93</td></tr>
<tr><td>Post-seismic at 24.9 °C</td><td colspan="2">123.87</td><td colspan="2">124.70</td><td colspan="2">117.80</td></tr>
<tr><td colspan="7">d) High voltage power frequency withstand test for power circuit, 28 kV for 60 seconds</td></tr>
<tr><td>Test condition</td><td colspan="2">R to Y phase</td><td colspan="2">Y to B phase</td><td colspan="2">B to R phase</td></tr>
<tr><td>Pre seismic</td><td colspan="2">withstood</td><td colspan="2">withstood</td><td colspan="2">withstood</td></tr>
<tr><td>Post seismic</td><td colspan="2">withstood</td><td colspan="2">withstood</td><td colspan="2">withstood</td></tr>
</table>

3.5 Acceptance Criteria

12 kV metal enclosed AC switchgear panel retained its structurally integrity. No visual damage, dislocation of components, crack or permanent deformation noticed. Change in resonance frequencies after seismic qualification is marginal, which forms quantitative data for proving structural integrity of test sample. Based on strain induced due to multi-frequency time history vibration stress levels are computed, which are less when compared to material yield stress. Change in structural integrity of operating mechanism in circuit breaker due to vibration will be depicted by change in opening and closing time measurement. Change in operating time of circuit breaker is marginal and within limit. Loosing or crack in busbar can be found by resistance measurement, change in resistance is also within limits. Switchgear cubical withstood high voltage power frequency test. Also circuit breaker was in withdrawable condition after seismic vibration.

In addition to pre and post-performance evaluation, functional performance of switchgear during multi-frequency vibration test was carried out. Circuit breaker was able to maintain its status (ON condition) during seismic vibrations. No change in status of auxiliary contacts observed.

12 kV metal enclosed AC switchgear panel was maintaining its functionality during and after the simulated earthquake event and meets the standard requirements.

4. Conclusions

Seismic qualification by shake table method and functional verification required before and after seismic test is presented in this paper. In case of metal enclosed switchgear, stress on load bearing members due to earthquake is less compared to limiting value of yield stress of material. Maximum strain induced due to multi-frequency seismic vibration on structural member of cubical under test is +96.78 and -192.70 micro strain which is less than the yield strength. Hence, mechanical failure is rarely noticed. But functioning of equipment during and/or after earthquake is the major concern. Results of resonance search test shows natural frequency of high voltage switchgear panel is 4.06 Hz which falls in high energy band of required response spectrum i.e. 1.10 Hz to 8.00 Hz. This is the major cause for functional failure in metal enclosed switchgear. Functional capability of equipment during earthquake can be verified exclusively by seismic qualification by shake table method.

5. Acknowledgement

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