Seismic Qualification of Instrument Transformers

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LISBOA 2012

SUMMARY:
Post-earthquake surveys have clearly shown that the substation equipment are vulnerable to severe earthquake shaking. Substation equipment like Circuit breakers, lightning arresters, current and voltage transformers have suffered severe damage during earthquakes since these equipment consists of porcelain elements. Hence it is very important that these equipment need to be designed to withstand site specific postulated earthquakes and subsequently tested for seismic qualification. An attempt is made to evaluate ground motion amplification by the supporting structure at the bottom of the porcelain component in a typical 220 kV Instrument Transformer. Ground motion amplification obtained from analysis and shake table tests is compared.

Keywords: ground motion amplification, dynamic characteristics, shake table test.

1. INTRODUCTION

Post-earthquake surveys have clearly shown that the substation equipment are vulnerable to severe earthquake shaking. Power utilities are taking utmost care to ensure reliability of electrical equipment and their supporting structures against vibrational hazards due to earthquakes. Hence Equipment and supporting structures of substations located in seismically sensitive regions have to be designed to withstand possible earthquakes.

Procedure recommended by the standards to qualify the seismic design of equipment includes both analytical simulations using numerical methods based on Finite element analysis and shake table testing. Analysis is resorted to only if shake table testing is not possible because of the limitation of the test system. Standards recommend an amplification factor of 2 to ground motion, if it is not possible to mount entire substation equipment on the shake table because of its size and weight and the equipment is tested without the supporting structure.

Seismic response of individual substation equipment needs to be evaluated to ensure reliability and safety of electrical transmission and distribution systems after an earthquake. Attempts have been made in this paper to compare the prediction of seismic response of a 220 kV Instrument Transformer by analytical method with the results of shake table tests. In addition, the amplification factor obtained from Finite Element Analysis and shake table tests are compared. The most natural and widely accepted testing concept for seismic qualification is the use of a shaking table. An Instrument transformer of 220kV had been chosen in this study for shake table testing and finite element analysis. The Instrument transformer is mounted on the Tri-axial shake table and exploratory and seismic tests have been carried out.

Exploratory tests normally described as resonance search tests are carried out on the equipment to determine its dynamic characteristics. Strain gauges are mounted on pre-identified locations on the Porcelain Element and supporting structure to measure the maximum stresses induced at the identified locations during seismic testing. In order to record the response time history and to identify the resonance frequencies number of accelerometers are mounted on the test specimen along all the three axes. The deflection at different locations are measured using laser sensors. Functional and vibrational response parameters are continuously monitored during seismic testing.

The numerical model of the Instrument transformer has been developed using PATRON and the dynamic characteristics and its seismic responses have been evaluated using FEA software NASTRAN. The damping value obtained from the experiment is used in the finite element analysis. The analytical results and experimental results are compared. The details of this study carried out on Instrument transformer, the recommendations made in connection with seismic qualification of substation equipment and the conclusion drawn are clearly brought out in this paper.

2. SUPPORT STRUCTURE

The performance of equipment and structures during earthquake depends on their configuration, strength of construction, ductility and their dynamic properties. Lightly damped structures having one or more natural modes of oscillation within the frequency band of ground excitation may experience considerable amplification of forces, component stresses and deflections. The satisfactory operation of substation during and after an earthquake depends on the survival, without malfunction of many diverse type of equipment. Individual equipment needs to be properly engineered. In addition, their anchorages and interconnections need to be well designed**.** The substation equipment are mounted on steel frames or concrete poles to maintain prescribed electrical clearances. These structures have a very significant effect on the motion that the supported equipment experience during an earthquake. The acceleration that the equipment experiences on a structure can be several times more severe than the ground acceleration. During qualification it is generally desirable to have the equipment mounted or modeled in the identical manner as it would be in its in-service configuration. When the equipment is tested without the 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. This paper deals with theoretical and experimental studies carried out to evaluate the seismic response of a typical 220 kV Instrument Transformer.

3. SEISMIC QUALIFICATION OF SUBSTATION EQUIPMENT

The shake table test is economic, tangible, and reliable validation test to assess the seismic safety and reliability of structures and equipment. Specimens of interest are mounted on the shake table and tests are conducted simulating design or postulated earthquakes. Extensive shake table tests are conducted at many research and academic institutes to validate earthquake resistant design of civil engineering structures and to qualify electrical equipment, control systems, switching relay banks, electrical control panels etc., To prevent failure of substation equipment and thereby ensure reliable power supply after earthquake, the International standards like International Electro technical commission (IEC) TR 300, Standard 61463 and Institute of Electrical & Electronic Engineers (IEEE) Std. 693 recommend testing of substation equipment along with the support structure for the site specific response spectra or peak ground acceleration using Shake table. They define qualification seismic levels, qualification procedures and acceptance criteria of all components of substation. Seismic levels have to be identified before test based on voltage capacity rating, physical properties and the seismic zone. The IEEE Standard recommends that sites with projected ground motions above 0.1g should have their equipment seismically qualified. One of the most effective ways of reducing earthquake damage for new installations is to use equipment that has been seismically qualified.

3.1 Resonance search test

A typical 220 kV Instrument transformer has been identified for shake table tests and finite element analysis. The Instrument transformer with support structure was mounted on the Tri-axial Shake table.

Accelerometers were mounted on top and bottom part of the porcelain element and at the top of the support structure to monitor and record dynamic response of the test specimen. Sine sweep test (Resonant frequency search test) was conducted on the equipment varying the frequency at the rate of one octave/minute from 1 Hz to 50 Hz maintaining acceleration at constant magnitude of 0.3g to determine the resonant frequencies and damping of the equipment. The shake table resonance search parameters are shown in Table 3.1. Structural response in terms of acceleration and strain has been monitored after mounting strain gauges and accelerometers at the pre-identified locations. The data obtained from this test are an essential part of an equipment qualification. Sine sweep test was conducted in both vertical and horizontal axes. Resonance frequencies in all the three axes were identified in the frequency range of 1.0 Hz to 50 Hz. The resonance frequencies are shown in the Table 5.2.

Table 3.1: Parameters for sine sweep test

1	Type of vibration	Sinusoidal sweep
2	Axis of vibration	X, Y & Z
3	Frequency (range)	1.0 to 50 Hz
4	Acceleration (Peak)	3.0 m/s^2
5	Sweep rate (Logarithmic)	1.0 Oct/minute
6	Number of Sweeps	One
7	Status of test sample during testing	Non-energized

Damping was determined using half power band width method. A typical damping calculation from the frequency response curve is shown in Fig.3.4.

3.2 Shake table tests

Standards recommend different procedures to qualify the substation equipment using shake table tests. The IEEE Standard 693-2005, "Recommended Practice for Seismic Design of Substations," addresses all aspects of the seismic design of substations. It clearly defines qualification seismic levels, qualification procedures, and acceptance criteria. The seismic resistance of the equipment to the stipulated response spectra corresponding to the seismic zone is evaluated for seismic qualification. During qualification test, seismic stimulation waveforms are generated to produce a Test Response Spectrum (TRS) that closely envelops the Required Response Spectrum (RRS) over the frequency range of interest using multiple-frequency input. The waveform or the compatible time history should have peak acceleration equal to or greater than the RRS ZPA. The RRS are usually specified at several levels of damping. Some utilities specify sine sweep test varying the frequency from 0.1 Hz to 33 Hz at a constant acceleration of magnitude equal to an arbitrary percentage of acceleration due to gravity, in the absence of National Standards recommending the seismic qualification level corresponding to various seismic zones.

The test specification for seismic qualification of Instrument Transformer prescribed a base acceleration of 0.3g in the frequency range of 0.1 Hz to 33 Hz for duration of 30 seconds. The test specimen is mounted on a tri axial shake table of size 3m x 3m with a payload capacity of 10,000kg established at Earthquake Engineering and Vibration Research Centre at Central power Research Institute, Bangalore. Instrument transformer mounted on shake table is shown in Fig.3.1. Table time history graphs which are given as input to the shake table are shown in Fig.3.2 and Fig.3.3. The response at top of the support structure and base of the porcelain equipment is monitored and recorded by mounting accelerometers at the corresponding locations. The amplification of base acceleration by the structure at the base of porcelain component at different frequencies is identified.

Figure 3.1. Instrument Transformer mounted on Shake Table.

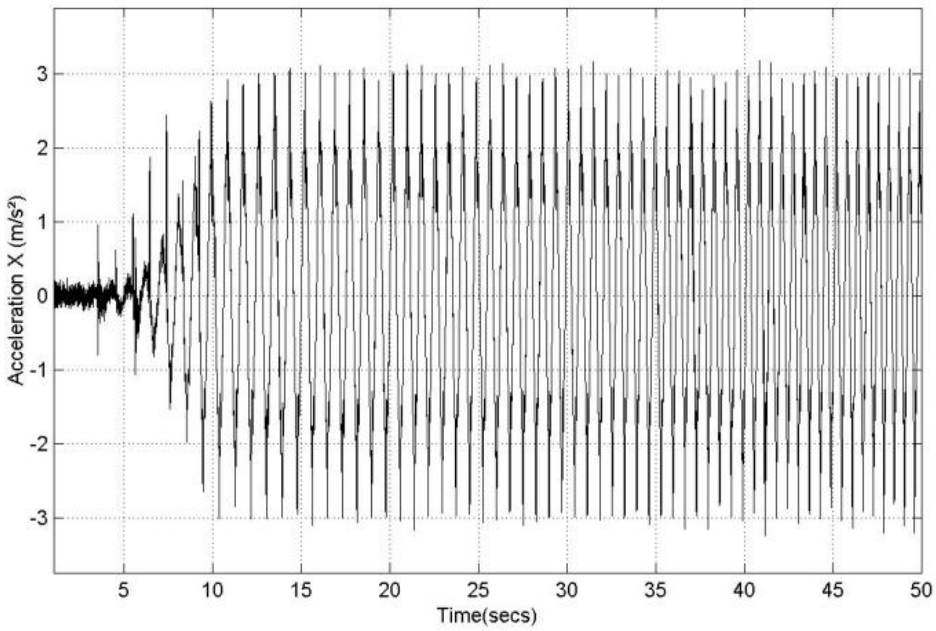

Figure 3.2. Table time history in longitudinal axis

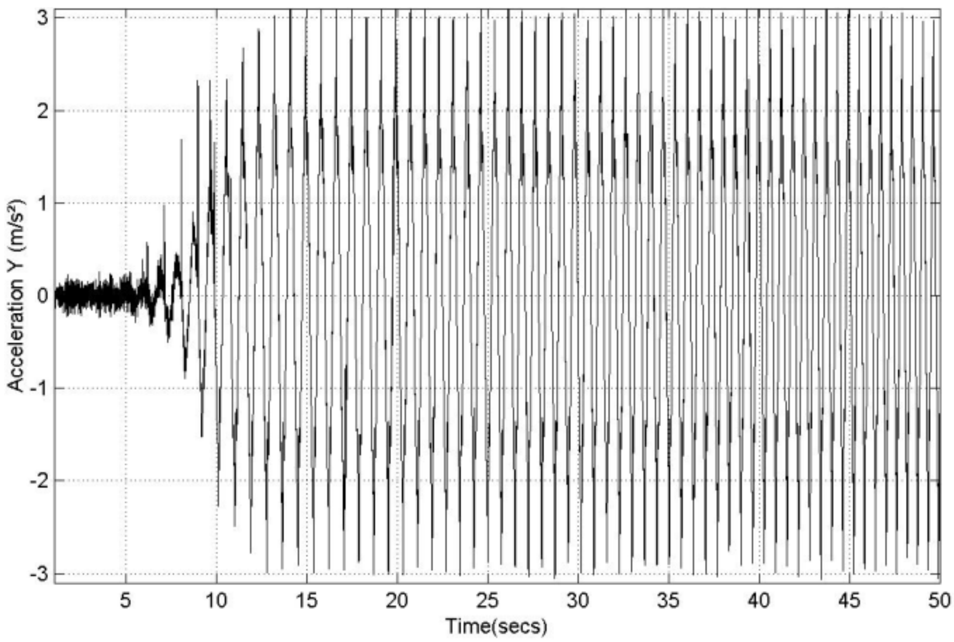

Figure 3.3. Table time history in transverse axis.

Minimum damping ratio obtained from structural response is considered as damping constant of the Instrument Transformer among transverse and longitudinal directions. The formula for identifying damping ratio using half power band width method is shown below Eqn.3.1. Damping ratio of 8% is obtained by using half power band width method shown in the Fig. 3.4. can be used for dynamic analysis of finite element model.

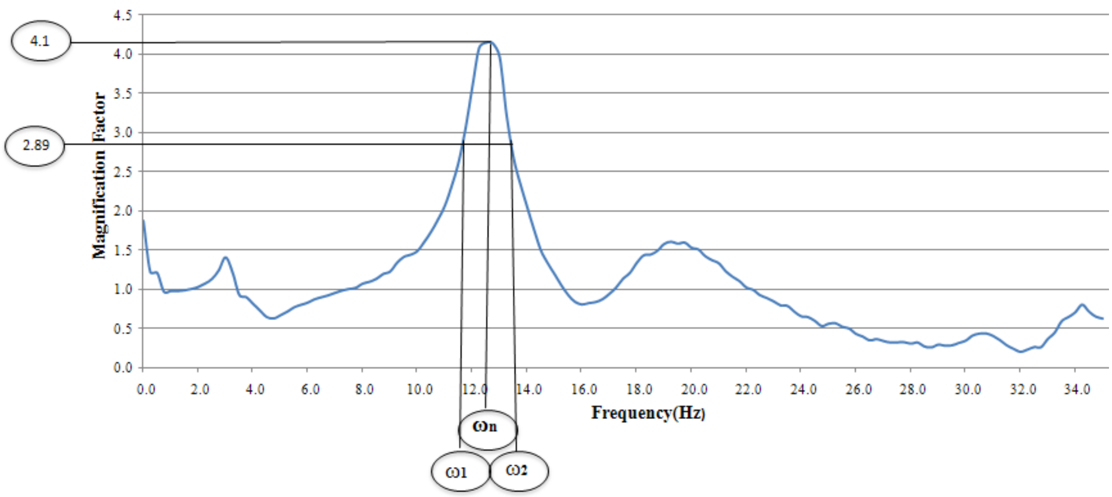

Figure 3.4. Damping ratio by half power band width method.

$$\xi = \frac{\omega_2 - \omega_1}{2 \times \omega_n} \times 100 \tag{3.1}$$

$$= \left[\frac{13.5 - 11.5}{2 * 12.5}\right] * 100$$

$$= 8\%$$

4. FINITE ELEMENT ANALYSIS

The support structure and the equipment Instrument transformer were appropriately modeled and analyzed using NASTRAN. It is very complex to model all the electrical instruments in any substation equipment for finite element analysis. Assumptions are introduced in numerical modeling to reduce complexity of the problem. A finite element model was developed considering appropriate mass distribution and stiffness characteristics of the structural components including porcelain elements as shown in Fig.4.1. The support structure with bracings is modeled using beam elements. Porcelain hollow cylinders are modeled as solid elements and the oil tank at the top and terminal assembly at the bottom are modeled as shell elements. The joints between sub-elements are also appropriately modeled. Frequency response analysis was carried out to identify the resonant frequencies and the corresponding mode shapes. Response of the finite element model for a ground acceleration of 0.3g was evaluated using software NASTRAN. Structural damping value obtained from the experimental investigation was considered for analysis. From the seismic response of the equipment and the structure, ground acceleration amplification at the base of Instrument Transformer termed as amplification factor, i.e., the ratio of acceleration at the base of the Instrument Transformer (response) to the ground acceleration (input) at the base of the mounting structure was evaluated from the FE analysis.

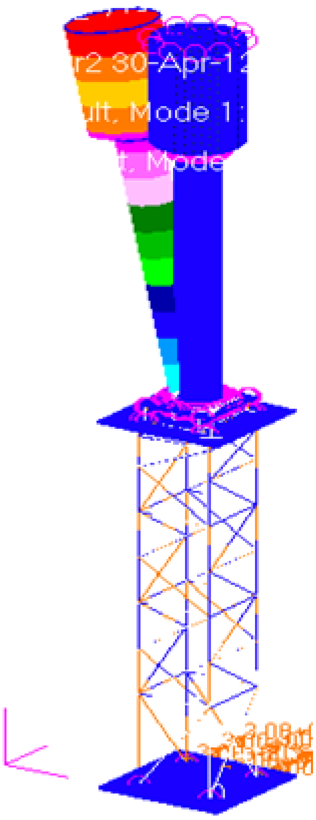

Figure 4.1. Finite element model-First mode along x-axis

5. RESULTS AND DISCUSSIONS

The resonant frequencies obtained from the Experimental investigation using Shake table and analysis using NASTRAN software are compared in Table 5.1. The damping coefficients obtained from shake table tests are used in finite element analysis. The resonant frequencies obtained from the analysis compare well with the experimental values. It clearly validates the accuracy of finite element model developed using the above software.

Table 5.1: Resonance frequencies of 220kV Instrument Transformer

Direction	Shake Table Test	FE Analysis
x axis (Horizontal)	2.8Hz,12.8Hz	3.0Hz,12.2Hz
y axis (Horizontal)	3.1Hz,13.1Hz	3.0Hz,12.6Hz
z axis (Vertical)	No resonance found	No resonance found

The amplification factor at the top of porcelain cylinder obtained from shake table tests and finite element analysis for a frequency range of 1 Hz to 33 Hz along X and Y axes are shown in Fig.5.1 and Fig.5.2.

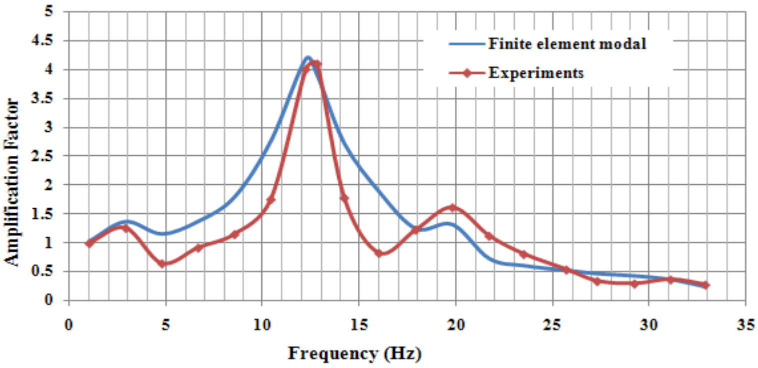

Figure 5.1. Amplification factor at top of the porcelain cylinder along X- axis

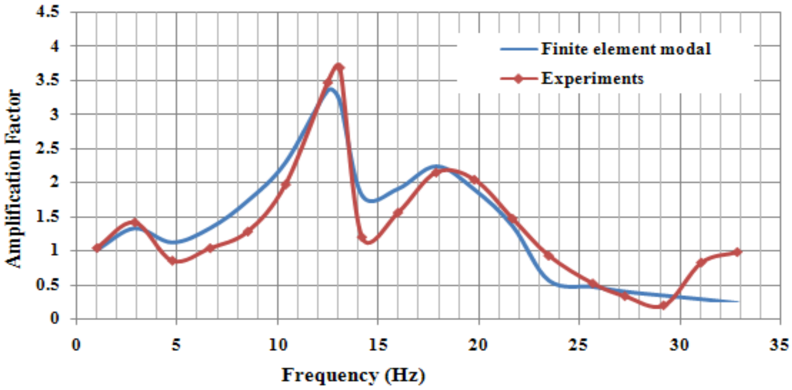

Figure 5.2. Amplification factor at top of the porcelain cylinder along Y- axis

Amplification factor at the bottom of the porcelain cylinder is obtained from the shake table tests and dynamic analysis using NASTRAN is tabulated in Table 5.2.

Table 5.2: Amplification factors at the bottom of the porcelain

Direction	Experiments	Finite element model
Longitudinal	4.1	4.2
Transverse	3.6	3.4

The response of the Instrument transformer at the bottom flange of Porcelain component recorded during shake table by mounting accelerometer and the corresponding response obtained from the finite element analysis are shown in Fig. 5.3. It can be seen that the response predicted by the analysis closely matches well with the shake table test results. This clearly confirms the adequacy of numerical simulations

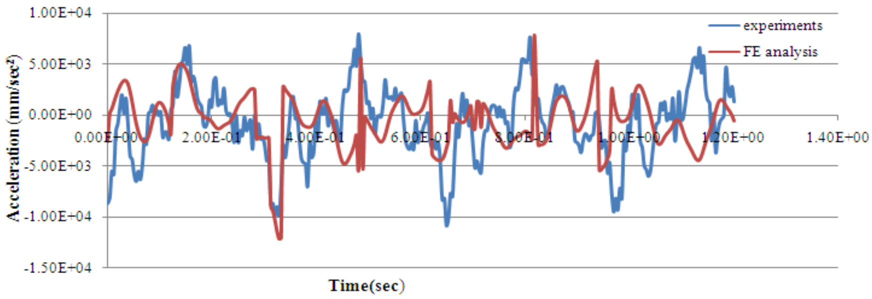

Figure 5.3 Response Time history at the bottom flange of the porcelain component

6. CONCLUSIONS

A series of tests have been performed using shake table to determine the seismic performance of structure and equipment. Finite element model of the Instrument Transformer was developed and its seismic response was obtained using NASTRAN software. Results of analytical and experimental studies on seismic response of a typical 220 kV Instrument Transformer are brought out in this paper. Results of Finite element analysis compare well with that of shake table tests.

For seismic qualification using shake table tests, Standard IEEE 693-2005 recommends an amplification factor of 2.5 for both the axes if equipment alone was tested without the support structure. Finite element analysis prior to shake table tests was preferable to evaluate precise amplification factor for seismic qualifications. The above study demonstrates that the Instrument Transformer can be modeled and analyzed with sufficient accuracy using finite element software like NASTRAN. Prior to seismic qualification of Instrument Transformer by shake table tests, it is preferable to analyze the equipment with support structure to identify the relevant amplification factor and its seismic withstand capacity to avoid failure during shake table tests.

ACKNOWLEDGEMENT
The authors gratefully acknowledge the encouragement of Shri. N. Murugesan, Director General, CPRI in bringing out this technical paper.

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