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Seismic Performance of 245 kV Current Transformer

Srujana N*, Ramesh Babu R** and Katta Venkataramana***

Substation equipment, whose natural frequencies lie in the normal frequency range of earthquake ground motion, is particularly vulnerable to damage by seismic events. Electric power systems are expected to be functional during and after major earthquakes and it is vital to sustain economic activities and assist recovery, restoration, and reconstruction of the damaged structures and equipment during earthquakes. Current transformer (CT), usually having a narrow long porcelain insulator, is the most vulnerable part subjected to earthquake. This paper evaluates amplification factor in terms of acceleration from the ground to top of the support structure where the current transformer is mounted. Sine sweep tests are conducted on current transformer with support structure to evaluate its dynamic characteristics using shake table tests. The ground motion amplification obtained from finite element analysis and shake table tests is compared.

Keywords: *Current transformer, Amplification factor, Shake table test.*

1.0 INTRODUCTION

The performance of equipment and structures during earthquake depends on their configuration, strength of construction, ductility and their dynamic properties [1]. 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 [2]. 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.

Earthquakes are major destructive forces to substation equipment involved in power distribution and transmission industry by upsetting the porcelain components. The substation equipments seismically qualified in laboratory showed a very weak post earthquake performance in the field [3]. The failure in porcelain part creates interruption in power distribution. To ensure reliable performance in the field, precise seismic qualification level needs to be specified.

The divergence of post earthquake field performance of current transformers from their laboratory performance demand researchers to revise the experimental methods adapted on shake-table based on international standards [4]. The paper deals with theoretical and experimental studies on dynamic behavior of a 245 kV Current Transformer. The ground motion amplification obtained from finite element analysis and shake table tests is compared.

*Ph.D student, Dept. of Civil Engineering, NITK, Mangalore-575025, Email: n.srujana@gmail.com
**Additional Director, Earthquake Engineering and Vibration Research Centre, CPRI, Bangalore. E-mail: rbabu@cpri.in
***Professor, Dept. of Civil Engineering, NITK, Mangalore-575025. Email: ven.nitk@gmail.com

2.0 RECOMMENDED PRACTICE FOR QUALIFICATION CRITERIAN FOR SUBSTATION EQUIPMENT

Static analysis, static coefficient analysis, dynamic response spectrum analysis, time history testing, sine beat testing and static pull testing are the methods used to qualify the electrical equipment. The use of seismic response spectra as a means for qualifying the equipment either by calculation or by test has become the most widely accepted method.

Substation equipments are normally mounted on support structures. These structures have a very significant effect on the motion that the supported equipment experiences 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.

2.1 Qualification Without Support

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. The amplification value used in testing shall be the amplification value multiplied by 1.1.

2.2 Qualification with Support

When equipment is mounted on a support or a variety of supports and the parameters of the support(s) are not known, the qualification will be acceptable if the equipment is mounted or modeled without the support and the qualification is conducted at 2.5 times the requirements stipulated in the relevant standards. An amplification of 2.5 should be considered in the shake-table test or analysis. In the analysis, the support structure should be such that the supports do not amplify the loads at the base of the equipment greater than 2.25 times the base accelerations and the support(s) shall meet all requirements of recommended standards.

This paper deals with theoretical and experimental studies on seismic response of a typical 245 kV Current Transformer. A series of tests have been performed using Tri-axial shake-table to determine the dynamic characteristics of structure and seismic performance of the structure and equipment. The results of Shake-table tests and those obtained from analytical models have been compared.

3.0 SHAKE-TABLE TEST

Shake-table test is more realistic method of earthquake testing than pseudo-dynamic method. The shake-table test is economic, tangible, and a reliable validation test to assess the seismic safety and reliability of structures and equipment. Specimens of interest are mounted on the table and tests are carried out simulating design or postulated earthquakes. The dynamic behavior of the structure or equipment and its damage pattern under earthquake can be reproduced. Extensive shake-table tests are conducted at many research and academic institutes to study earthquake-resistant design of civil engineering structures and to qualify electrical equipment, control systems, switching relay banks, electrical control panel, etc.

A 245 kV Current transformer with support structure was mounted on the Shake table as shown in Figure 1. Accelerometers were mounted on top and bottom part of the porcelain element and at the top of the support structure to monitor and record the dynamic response of the current transformer. 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 33 Hz maintaining acceleration at constant magnitude of 0.1 g as shown in Table 1 to determine the resonant frequencies and damping of the equipment. The data obtained from this test are an essential part of an equipment qualification; however, the test does not constitute a seismic test qualification by itself. Sine sweep test was

FIG.1 245 kV CURRENT TRANSFORMER WITH SUPPORT STRUCTURE MOUNTED ON TRI-AXIAL SHAKE-TABLE

TABLE 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 35 Hz
4	Acceleration (Peak)	1.0 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

conducted in both vertical and horizontal axes. Damping was determined using half power band width method.

The seismic test was conducted on the current transformer for a constant ground acceleration of 0.3g for a duration of 30 seconds. The seismic response of the equipment and the structure was recorded. The amplification of ground acceleration by the structure at the bottom level of the porcelain element of current transformer was determined.

4.0 NUMERICAL MODELING AND ANALYSIS

The support structure and the equipment were appropriately modeled and analyzed using NASTRAN. Assumptions are introduced in the modeling to reduce complexity of the problem. Oil sloshing effects and complex inner part connectivity were not considered. Porcelain was the critical part in the entire model.

The equipment was divided into top, middle and bottom parts. The support structure was modeled as steel truss. Top part includes bellow cover and oil tank; middle part includes porcelain component filled with oil and bottom part includes base of the CT. Bellow cover and dome have been modeled as shell elements. It was assumed that the inner parts are rigidly connected to the walls of the bellow cover and dome. Hollow porcelain cylinder was modeled with solid elements. Joint between the porcelain and the dome is modeled with multipoint constraints (MPC). These MPCs are created at the bolt locations. Base of the equipment was modeled with solid elements. Weight of the transformer oil was considered in the analysis but not the sloshing effects. Mounting condition of the Current Transformer on steel support structure was also simulated. The finite element model developed using the preprocessor PATRAN is shown in Figure 2.

Assumptions are taken in case of inner connections and transformer oil since they are rigidly connected to the walls and oil filled

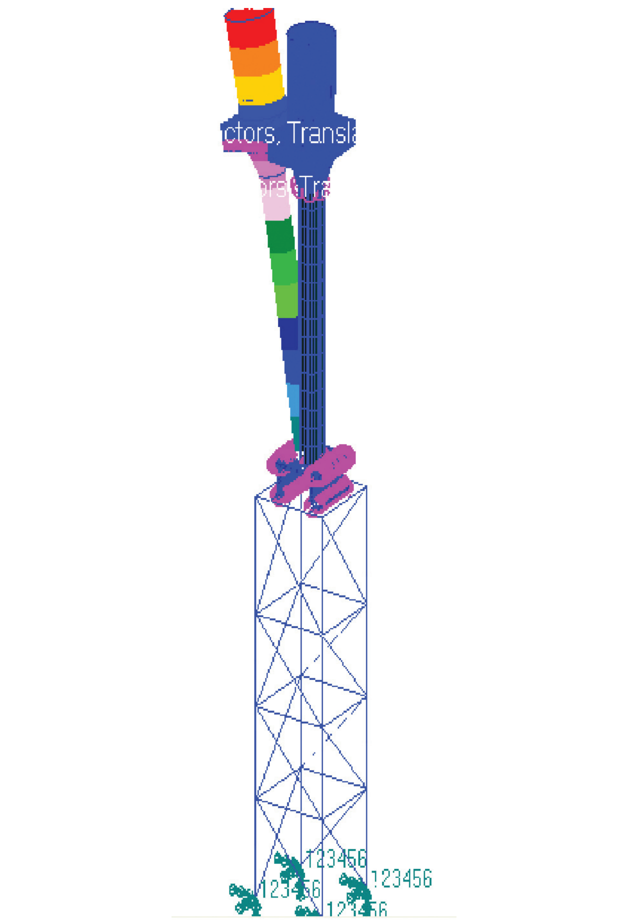

FIG. 2 FINTE ELEMENT MODEL OF 245 kV CURRENT TRANSFORMER

to the full extent to the nib and mainly those are covered with outer layers like steel and porcelain. Generally, power losses occur at the porcelain insulation joints connected to the conductors and joints at porcelain insulation to the base of the transformer. The concentration of the qualification study is on joint connections which are likely to cause power disruption under vibration. This study is done through ground motion amplification under applied ground motions.

MSC NASTRAN was used as analytical tool for seismic qualification. The finite element model was subjected to frequency response the analysis. Structural damping value obtained from the experimental investigation was considered for analysis. Resonant frequencies and the corresponding modes are identified. Ground acceleration of 0.3 g for the frequency range 1–50 Hz was applied as seismic load at the base of the support structure i.e. at the base of the steel support structure. Seismic response of the equipment and the structure was obtained. Ground acceleration amplification at the base of current transformer termed as Amplification factor, the ratio of acceleration at the base of the current transformer (response) to the ground acceleration (input) at the base of the mounting structure was evaluated from the FE analysis.

5.0 RESULTS AND DISCUSSIONS

The resonant frequencies obtained from the experimental investigation using shake-table and analysis using NASTRAN software are compared in Table 2. 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 2

RESONATING FREQUENCIES

Direction	Resonating Frequencies	
	Experimental	**Analytical**
Transverse-X	10.5Hz	11Hz
Transverse-Y	11.0Hz	11.5Hz
Longitudinal-Z	No resonance	26Hz

Amplification factor obtained from the shake-table tests with a constant ground acceleration of magnitude 0.3 g in the frequency range between 1 and 50 Hz and amplification factor evaluated from the analysis along the two horizontal axes are shown in Table 3. In the finite element analysis, the damping value obtained from the sine sweep test was considered. Amplification factor obtained from experiments compares well with that of analysis.

TABLE 3

AMPLIFICATION FACTORS

Direction	Ground acceleration amplification	
	Experimental	**Analytical**
Transverse-X	2.6	2.7
Transverse-Y	2.8	2.7

6.0 CONCLUSIONS

A series of tests have been performed using shake-table to determine the seismic performance of the structure and equipment. Finite element model of the Current transformer was developed and its seismic response was obtained using NASTRAN software. Results of analytical and experimental studies on seismic response of a typical 245 kV Current Transformer are brought out in this paper. From Figures 3 and 4 it can be seen that results of Finite element analysis compare well with that of shake table tests.

Shake-table test results have shown that the ground acceleration was amplified 2.6 times at the top of the support structure in x-direction and 2.8 times amplified in y-direction. Finite element analysis predicted ground acceleration amplification at the top of the structure as 2.5 along x-axis and 2.7 along y-axis. Both analysis and experiments have clearly shown that the amplification may vary with different rating of transformers as well as manufacturers.

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.

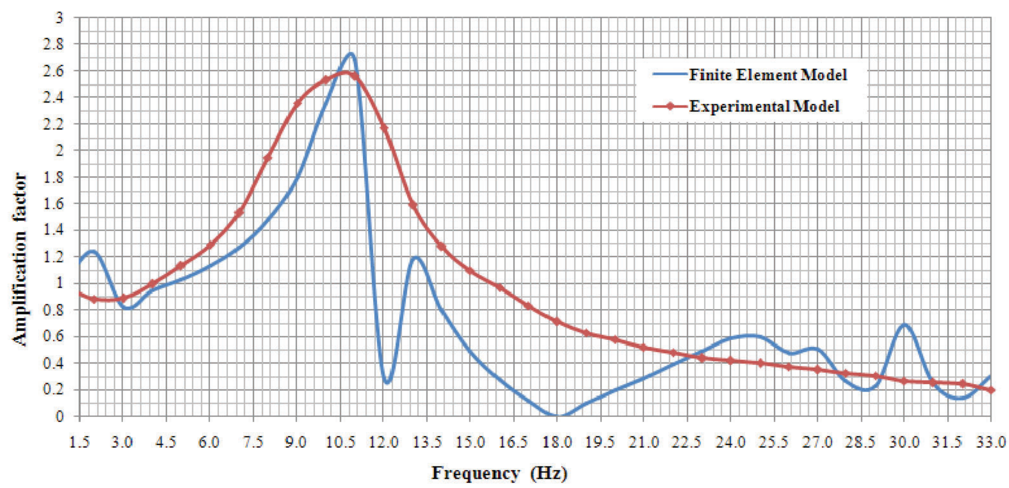

FIG. 3 AMPLIFICATION ALONG X-AXIS AT THE BASE OF THE CURRENT TRANSFORMER

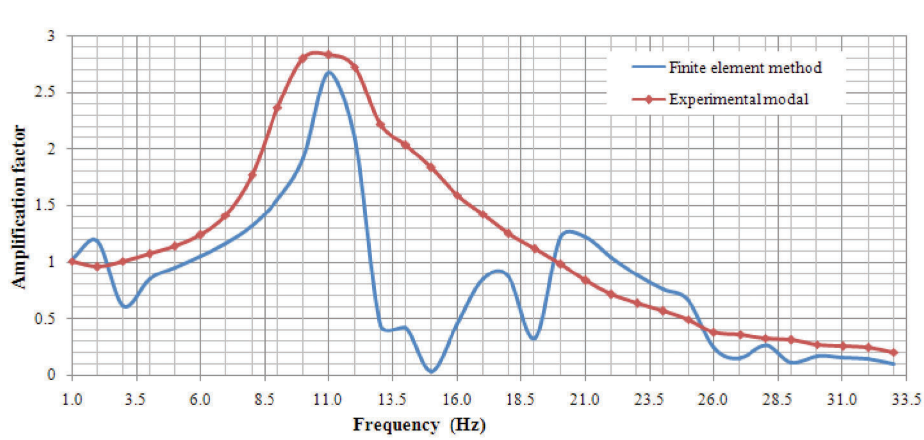

FIG. 4 AMPLIFICATION ALONG Y-AXIS AT THE BASE OF THE CURRENT TRANSFORMER

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