The Journal of CPRI,
Vol. 9, No. 3, September. 2013 pp. 443-448

Shake Table Experiments of Surge Arrester for Evaluation of Ground Motion Amplification

N Srujana*, R Panneer Selvam**, R Ramesh Babu***, Katta Venkataramana****

The support structure of a surge arrester within the substation is considered for the experimental and finite element study. Support structures are generally used in a substation mainly for the electrical ground clearance purposes but also it protects the mounting equipment with respect to earthquake loads. The paper is aimed to find out the acceleration amplification levels at base of the support structure at severe earthquake loadings even when it is mounted on steel support structures. Seismic tests are carried out experimentally on shake table. The behavior of the support structure is found satisfactory. No material losses are resulted. Finite element studies are also included in the paper. The finite element model predictions are agreeable to the experimental results.

Keywords: *Surge arrester, ground motion amplification, shake table tests.*

1.0 INTRODUCTION

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. 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 very weak post earthquake performance in the field. 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 substation equipment from their laboratory performance demand researchers to revise the experimental methods adapted on shake table based on international standards. The paper deals with theoretical and experimental studies on dynamic behaviour of a 624kV Surge Arrester. The ground motion amplification obtained from finite element analysis and shake table tests is compared.

2.0 OVERVIEW OF WORK DONE IN THIS FIELD

Chandrasekaran A.R and Singhal N (1984) [1] proposed a new test method based on dynamic

*PhD Student, Dept. of Civil Engineering, NITK, Mangalore-575 025, Email: n.srujana@gmail.com.
**EngineeringOfficer, Earthquake Engineering & Vibration Research Centre, CPRI, Bangalore, 560 080. Email: selvam@cpri.in
***Additional Director, Earthquake Engineering & Vibration Research Centre, CPRI, Bangalore, 560 080. Email: rbabu@cpri.in
****Professor, Dept. of Civil Engineering, NITK, Mangalore- 575 025. Email: ven.nitk@gmail.com.

response of the system during a postulated design earthquake to assess the earthquake withstand capability of the system using experimentally validated analytical models for 624kV surge arrester. The criterion uses a theoretical-cum-experimental approach. The experimental results of natural frequency and damping are utilized to evaluate theoretically the maximum response acceleration which would be expected to occur at various locations of the equipment.

Hatami et al., (2004) [2] : Thispaper deals with theoretical and experimental studies on 132kV Current Transformer model to develop analytical model for different heights and stiffness factors. The support mounting of the equipment plays a vital role as it changes the dynamic characteristics of the equipment. Based on empirical studies, it is identified that a current transformer without any interaction with other equipment is better positioned to withstand seismic shocks. Consequently, for Instrument Transformers, which have identical structure, supplementary shake table tests are not necessary, since a similar stress distribution for different voltage classes occurs. This allows a valuable prediction of their behavior.

Stefanov D (2007) [3] proved from his experimental studies that the lower cross section of insulating material porcelain on wheel supportsis observed to be vulnerable more to earthquakes. The wheel support show overturning tendency. Alternatively,he designed additional fixing devices to wheel supports to prevent possible overturns

3.0 SEISMIC QUALIFICATION OF SUBSTATION EQUIPMENT

Substations are with critical equipment positioned in generating and distribution-transmission stations for the protection of conductor lines, among others. The track record of past earthquakes indicates losses caused on account of damages to substation equipment during natural seismic disasters. In case of instrument transformers with support structures, ground motion at base of the support structure gets amplified several times while traversing to the base of the equipment. Amplified higher acceleration level induces maximum stresses in the insulator and in its attachments. Higher stress causes failure in porcelain cylinders. Therefore interruption in power supply causes loss of revenue as well. In most of the cases, retrofitting of a damaged system or reuse of damaged power equipment after repairs may not be possible. It is therefore important to design substation equipment to withstand testing rigors or severity of induced earthquake vibrations on shake table as per standards for qualification tests.

4.0 IEEE-693-2005: RECOMMENDED PRACTICE FOR SEISMIC DESIGN OF SUBSTATIONS

Seismic qualification to a structure is the evidence to safety assessment of structure at required levels of excitation. International standards like IEEE-693 provides seismic design recommendations for substation equipment, which clearly define the qualification seismic levels, qualification procedures and acceptance criteria for substation equipment.

Records of many a past earthquake had shown peak ground accelerations are not exceeding 0.5g and only in a few cases the peak acceleration touches. Precisely for the said reason, qualification is normally done by testing or by my method of analysis at the reduced levels of 0.5 g or below. These reduced levels are seismic qualification levels. 0.5g for high level and 0.25g for moderate seismic qualification level with each tied to a specific RRS. RRS defines the input motion used for testing, analysis when seeking a seismic qualification. The shape of RRS is a broad band spectrum. Although the RRS has taken the above effects into account, it has not been derived by enveloping response spectra from historical earthquakes included in the evaluation. It is the intent of this practice that equipment qualified to one seismic qualification level would remain functional after a seismic event corresponding to a level of shaking twice that actually tested. This level is defined as performance level. The performance levels and the corresponding seismic qualification levels are related to each other by a factor of 2.0. As per the standard, the applied ground motion at the base of the foundation amplifies through the support structure to the base of the bushing by 2.5 times of the applied ground motion.

When the 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 requirement specified in this recommended practice. The manufacturer shall include an amplification of 2.5 in the shake-table test or analysis. The users shall design the structures, once the parameters become known 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 the requirements of this recommended practice. When considering the amplification factors, the user should consider the complexity of the support motions, which may include translation, torsion, and rotation of the equipment.

Sometimes qualification of entire equipment with support structure is not possible due to the limitations of the shake table. In such cases 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 scale model of amplification value used in testing shall be 1.1.

5.0 QUALIFICATION BY SHAKE TABLE EXPERIMENTS

Shake table qualification involves resonance search tests (sine sweep) and seismic tests at the required frequency durations. Natural frequencies and corresponding local damping ratios are identified with the help of resonance search tests. Seismic tests are carried out on the structure as per IEEE-693 standard. During seismic qualification test, simulation waveforms are generated to produce a Test Response Spectrum (TRS) as an input to the shake table 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 Zero Peak Acceleration.

The qualification level of 0.3g input acceleration in the frequency range of 1Hz to 30Hz in the duration of 30sec is specified as per the standard IEEE-693 [4]. A 624kV-20k Asurge arrester with support structure is mounted on tri- axial shake table of 3mX3m with the payload of 10 tonne capacity (see Figure 1). The height of the support structure is 6.3m weighting 1400kg. The 624kV-20kA surge arrester contains stack of solid metal oxide varistors with a housing of wrapped silicone rubber compound inside the porcelain cylinder. Metal oxide varistors are rigidly arranged inside the hollow porcelain cylinders. It has total four numbers of porcelain insulators arranged in series. The total height of porcelain insulator is 1.8m with the weight 462kg. The porcelain cylinder is the major part of the equipment having huge weight and diameter covers 3.0m with wall thickness 40mm.

FIG.1 624KV-20MASURGE ARRESTER MOUNTED ON SHAKE TABLE.

Accelerometers are arranged at top of the support structure to measure acceleration response. Sine sweep tests are conducted on instrument transformer at 1 octave/min in between 1 to 33 Hz range of frequency of magnitude 0.3g as per the standard for earthquake applicable to transverse X and Y directions.

The sine sweep test specifications are given in Table 1. The data obtained from the sine sweep test are the essential part of an equipment qualification. Accelerometer locations are assumed at base of the surge arrester i.e., at the top of the support structure. In this study, bottom part of porcelain cylinder is considered as critical, based on past earthquake data. Amount of amplification is determined from digital analysis package for all the cases considered. Resonance frequencies and damping ratios are identified from the tests. Damping ratio of 0.05 is identified from the half power band width method. The concentration of the study is on connections between support structure and base of the transformer which is liable to cause equipment destruction under earthquake induced forces.

TABLE 1
PARAMETERS FOR CONTINUOUS SINE SWEEP TEST

1	Type of vibration	Sinusoidal sweep
2	Axis of vibration	X, Y & Z – axes
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

6.0 QUALIFICATION BY FINITE ELEMENT ANALYSIS

Modeling assumptions made are based on the premiss of indeterminate nature of fixity between inner part connections in the surge arrester. Hollow porcelain cylinder is modeled with solid elements. Joints between the porcelain insulators are modelled on the basis of Multi-Point Constraints (MPC) using connecting bolts. These MPCs created are represented in the drawings. The base of the model comprises of solid elements. Metal oxide blocks are assumed as rigid elements. The support structure is modeled with bar elements. Analytical software tool used is MSC - NASTRAN 2008. First and second modes of finite element models of surge arrester are shown in Figure 2 and Figure 3.

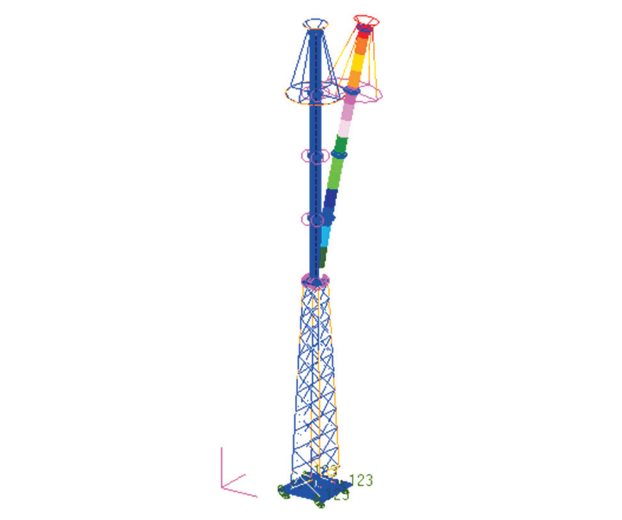

FIG. 2 624KV SURGE ARRESTER FINITE ELEMENT MODEL AT ITS FIRST MODE

Shake table input sine sweep of 0.3g is applied to the base of the model i.e., at the base of the steel support structure. Amount of ground motion amplification is calculated at the base of the instrument - transformer. Ground motion amplification at the base of instrument transformer is the ratio of acceleration at the base of the transformer to the acceleration at the base of the support structure. Natural frequencies are identified. Damping ratio obtained from the experimental shake table tests are used in the finite element analysis during evaluation of response accelerations.

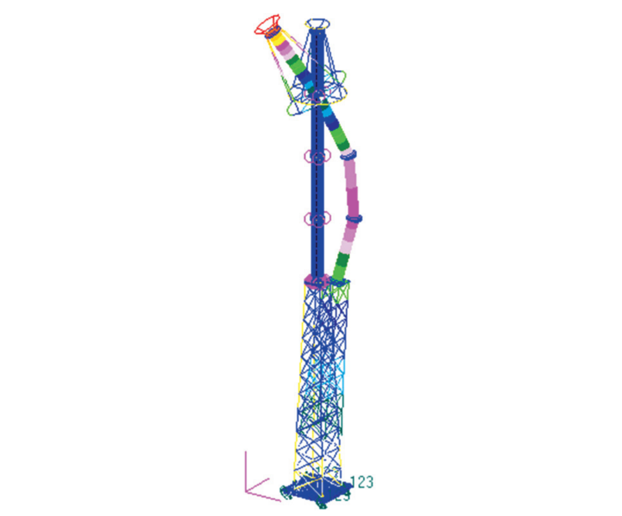

FIG. 3 624KV SURGE ARRESTER FINITE ELEMENT MODEL AT ITS SECOND MODE.

DISCUSSION OF RESULTS

The parameters worked out from the finite elmenent model-anlysis are in agreement with a high degree of correlation. Effects of the ground motion amplification at top of the support structure in transverse X and Y axes in finite element analysis and in shake table experiments conducted are compared in Figure 4 and Figure 5. A comparative study made between the amplified acceleration resulted at top of the support structure in X and Y axes (as a result of applied acceleration at the ground level, using shake Table) along with resonance frequencies drawn from shake table experiments and finite element analysis made on full scale Model of 624kV surge arrester is shown in Table 2.

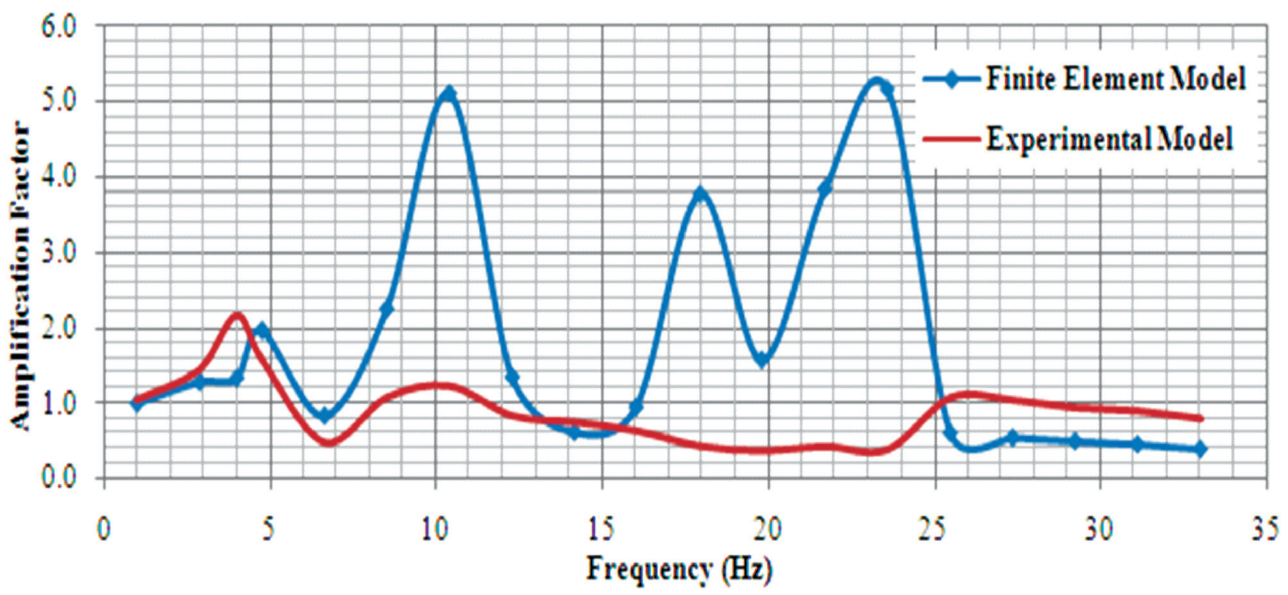

FIG. 4 RESPONSE AMPLIFICATION AT TOP OF THE SUPPORT STRUCTURE OF 624kV surge arresterin X-axis.

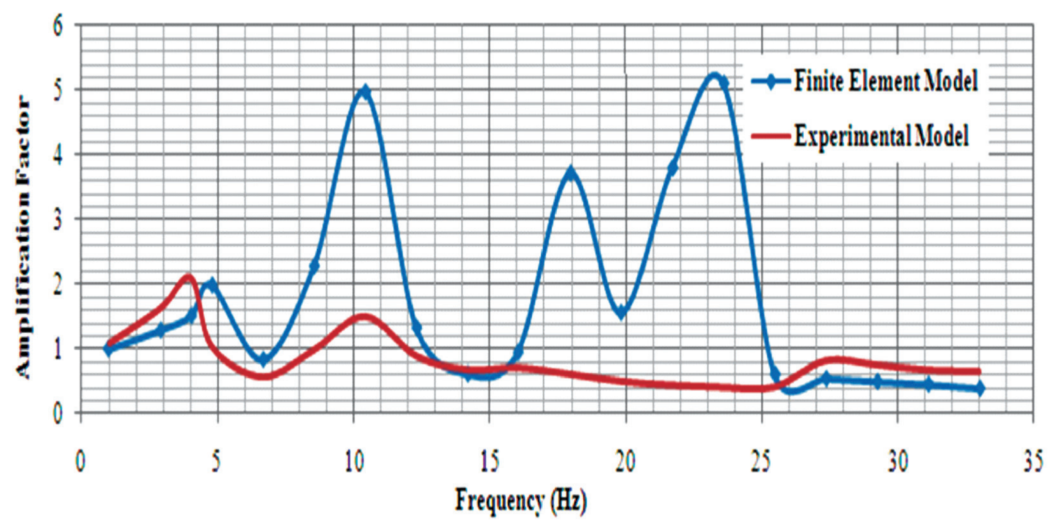

FIG. 5 RESPONSE AMPLIFICATION AT TOP OF THE SUPPORT STRUCTURE OF 624KV SURGE ARRESTERIN Y- AXIS.

TABLE 2				
DETAILS OF NATURAL FREQUENCIES AND AMPLIFICATION FACTORS OF 624KV SURGE ARRESTER				
Location of accelerometer	**Amplification with respect to acceleration**		**Natural frequencies**	
	Experiments	**FE Analysis**	**Experiments**	**FE Analysis (First two modes)**
Top of the support in X-axis	2.1	2.2	4.0Hz	0.5Hz, 4.5Hz
Top of support in Y-axis	2.0	1.9	4.0Hz	0.5Hz, 4.6Hz

1) Natural frequency of the full scale surge arresterfrom shake table experiments along X-axis and 4.0Hz to 4.0Hz in Y-axis.

2) In the finite element model analysis, First and second mode of resonance frequencies occurred at 0.5Hz and 4.5Hz along X and Y-axes.

CONCLUSIONS

1) Natural frequencies and amplification factors calculated from finite element analysis of the mode are by and large in agreement with the empirical results. Thus finite element analysis is preferable prior to shake table tests to evaluate precise amplification factor for seismic qualifications.

2) Acceleration amplification of 2.5 effected at the top of the support structure i.e. at the base of the porcelain cylinder, as determined based on the experimental studies is found to be sufficient to meet the recommended IEEE-693 testing norms. It is seen the amplification factor is

3) Arrived closer to 2.5 in the case of dampers application.

4) Mounting full scale model on shake table with support structure is difficult. Pre-identified appropriate amplification obtained from finite element model can be used in shake table as an input while qualifying the porcelain insulators experimentally for such models.

ACKNOWLEDGEMENT

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

REFERENCES

[1] Chandrasekaran, A. R. and Singhal, N. C., (1984) “Earthquake Resistance Capability Of Voltage Transformer” Journal of Energy Engineering, 110, Paper No. 18641.

[2] Hatami, M. Ghafory, M. and Hosseni, M., (2004) “Experimental and Analytical Study of a High Voltage Instrument Transformer” 13th World Conference on Earthquake Engineering, Vancouver, B. C. Canada, Volume 2, Paper No. 2550.

[3] Stefanov, D., (August 2007) “Analytical and Experimental Seismic Qualification of Three Types of Electric Transformers” Transactions, SMiRT 19, Toronto. Transformers” Transactions, SMiRT 19, Toronto.

[4] IEEE Standard 693-2005, IEEE Recommended Practice for Seismic Design of Substations.

[5] William T. Thomson, Marie Dillon Dahleh, Chandramouli P “Theory of Vibration with Applications” (1998), 105-131.