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Identification of Dynamic Characteristics of 12 kV Circuit Breaker under Earthquake Loading

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History of past earthquakes had demonstrated that structural failures in substations were non-recoverable unless huge amount of money and man power involves in it. A broad range of substation equipment are especially vulnerable to seismic vibrations and circuit breaker is one among them. Failure in circuit breaker results flow of excessive current in substation components than the respective ratings. Excessive current in substation components cause fire accidents along with power outages. The efficient way to resolve the problem is to analyze and identify the failure points over the earthquake vibrations before installing in the field. This paper discusses in relation to earthquake acceleration amplification of 12 kV circuit breaker used in substations. Shake table experiments are conducted on circuit breaker at higher seismic zone levels. The ground motion amplification obtained from finite element analysis and shake table tests is compared.

Keywords: *Circuit breaker, Ground motion amplification factor and Shake table experiments.*

1.0 INTRODUCTION

We are experiencing, approximately 20,000 earthquakes every year, or about 55 per day. The majority of these earthquakes are small, and we can expect about 16 major earthquakes in any year. Earthquakes of higher intensity are infrequent.

The wave frequency of minor earthquakes matches to the natural frequency of substation equipment. But according to the past earthquake data, damage severity of high voltage substation equipment is very high and it is even extended to large area through electric network connections. High voltage substation equipment includes current and voltage transformers, power transformers, circuit breakers, surge arresters etc. Porcelain insulators are functionally treated as key component in entire high voltage substation. Due to size and weight of the porcelain insulator cylinders, they are observed to be most vulnerable components in substation. As a result of structural damages like cracks on surface of porcelain and overturning of porcelain from the core line leads to lengthy power interruptions.

Substation equipments are generally mounted on tall steel truss support to allow electric clearance between the equipments. The ground acceleration from the base of the support amplifies several times to the top of the equipment. It means top of the equipment is subjected to earthquake acceleration several times higher than the acting ground acceleration at base of the steel support structure. Failure occurs if frequency of the earthquake coincides with resonating frequency of the entire substation equipment and support structure. National and International standard recommends simplified test procedures to be followed to predict the failure and structural behavior under seismic vibrations before field installations.

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The divergence of post earthquake field performance of circuit breakers 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 12 kV circuit breaker. The ground motion amplification obtained from finite element analysis and shake table tests is compared.

Significant research has to be done to improve the post earthquake performance of the high voltage substation equipment.

2.0 RECOMMENDED PRACTICE FOR QUALIFICATION CRITERIA FOR SUBSTATION EQUIPMENT

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

Substation equipment are normally mounted on support structures. 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.

2.1 Qualification without support

When the equipment is tested without the support, the shake-table base acceleration shall be amplified toreplicate 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 12 kV circuit breaker. A series of tests have been performed using Tri-axial shake table to determine the dynamic characteristics of structure and seismic performance of structure and equipment. The results of Shake table tests and those obtained from analytical models have been compared.

FIG. 1 12 kV CIRCUIT BREAKER WITH SUPPORT STRUCTURE MOUNTED ON TRI-AXIAL SHAKE TABLE.

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 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 panels etc.

A 12 kV circuit breaker with support structure was mounted on the shake table (shown in Figure 1). Accelerometers were mounted on top of middle insulator assembly to monitor and record 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–33 Hz maintaining acceleration at constant magnitude of 0.2 g for a duration of 30 secs to determine the resonant frequencies and damping of the equipment. Damping was determined using half power band width method. Parameters for Sine Sweep Test shown in Table 1.

Seismic test was conducted on the circuit breaker simulating the response spectra recommended in IS 1893:2003, corresponding to seismic Zone V at 5% damping level. The response spectra in the vertical direction is two-third of the horizontal response spectra. Seismic simulation was along all the three axes simultaneously. After few iterations, it is ensured that the test response spectra generated enveloped the required response spectra completely over the frequency range of 1 Hz–33 Hz for a duration of 30 secs.

The data obtained from this test are an essential part of an equipment qualification.

TABLE 1

PARAMETERS FOR SINE SWEEP TEST

1	Type of vibration	Sinusoidal sweep
2	Axis of vibration	X, Y & Z
3	Frequency (range)	1.0–35 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

The seismic response of the equipment and the structure was recorded. The amplification of ground acceleration by the structure at the top level of the porcelain element of circuit breaker was determined.

4.0 NUMERICAL MODELING AND ANALYSIS

The support structure and the equipment were appropriately modelled and analysed using NASTRAN. Assumptions are introduced in the modelling 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 support structure was modelled as steel truss. Porcelain insulator and control cubical box are modelled with appropriate elements. It was assumed that the inner parts are rigidly connected to the walls of the control cubical. Hollow porcelain cylinder was modelled with solid elements. Joint between the porcelain and the control cubical is modelled with multi point constraints (MPC). These MPCs are created at the bolt locations. After dveloping the analytical model, mass of individual component was verified with its actual mass measured using the digital load cell. Each set of porcelain cylinders are inter-connected with rubber and steel gaskets. Multipoint constraints were introduced at the nodes of connecting bolts of porcelain elements. The finite element model is developed using the preprocessor PATRAN is shown in Figure 2. Mounting condition of the circuit breaker with steel support structure was also simulated.

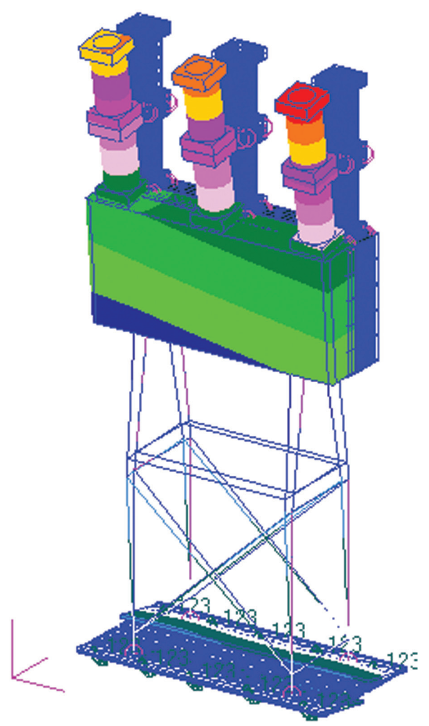

FIG. 2 FIRST MODE OF FINTE ELEMENT MODEL OF 12 kV CIRCUIT BREAKER.

Generally power losses occur at the porcelain insulation joints connected to the conductors and joint 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 analysis. Structural damping value obtained from the experimental investigation was considered for analysis. Resonant frequencies and the corresponding modes are identified. The response spectra corresponding to seismic Zone V of IS 1893–2002 assuming a damping value of 5% was fed as input to the software. The response of the equipment in terms of acceleration at the top level of middle insulator assemblies, the location at which the accelerometers were mounted during seismic qualification by shake table experiements is 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.

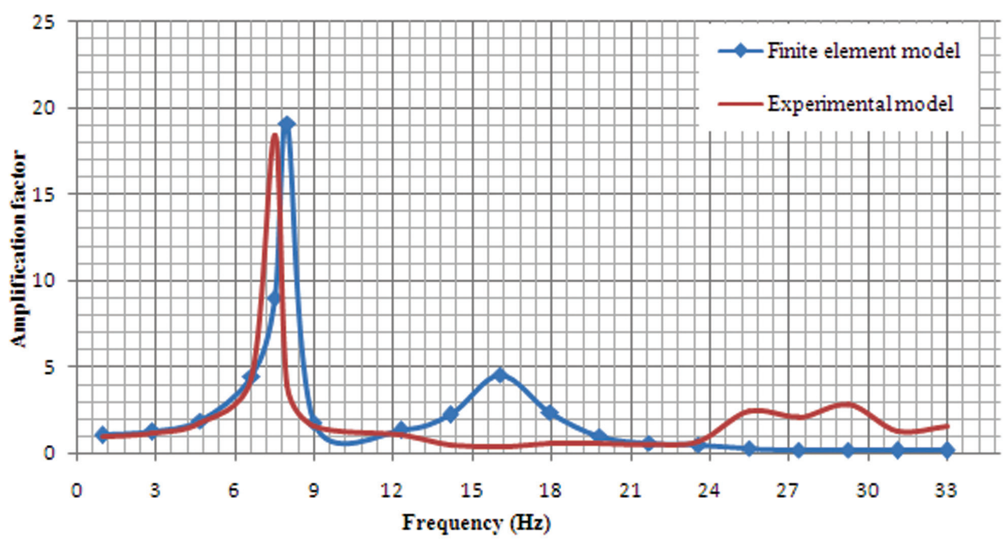

FIG. 3 RESPONSE AMPLIFICATION AT THE TOP OF THE PORCELAIN INSULATOR OF 12 kV CIRCUIT BREAKER IN X-AXIS.

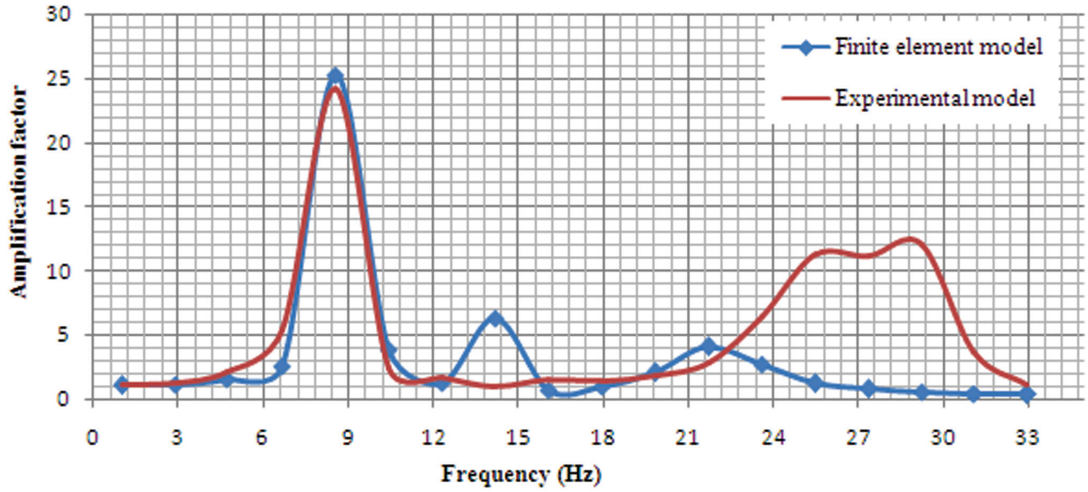

FIG. 4 RESPONSE AMPLIFICATION AT THE TOP OF THE PORCELAIN INSULATOR OF 12 kV CIRCUIT BREAKER IN Y-AXIS.

5.0 RESULTS AND DISCUSSIONS

The resonant frequencies obtained from the Experimental investigation using Shake table and analysis using NASTRAN software is 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	Experimental	Analytical
Transverse-X	8.0 Hz	8.2 Hz
Transverse-Y	8.0 Hz	8.5 Hz
Longitudinal-Z	No resonance	30 Hz

Amplification factor obtained from the shake table tests as per IS 1893:2000, response spectrum corresponding to Zone V at 5% damping level 1–33 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

Ground Acceleration Amplification		
Direction	**Experimental**	**Analytical**
Transverse-X	18.4	19.0
Transverse-Y	24.2	25.4

6.0 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 circuit breaker was developed and its seismic response was obtained using NASTRAN software. Results of analytical and experimental studies on seismic response of a typical 12 kV circuit breaker are brought out in this paper. Results of finite element analysis compares well with that of shake table tests.

Shake table test results have shown that the ground acceleration was amplified 18.4 times at the top of the porcelain insulator in X-direction and 24.2 times amplified in Y-direction. Finite element analysis predicted ground acceleration amplification at the top of the porcelain insulator as 19.0 along X-axis and 25.4 along Y-axis. Both analysis and experiments have clearly shown that the amplification may vary with different rating of transformers as well manufacturers.

The main objective of this research work is to evaluate the amplification factor at the base of the porcelain element, so that the most vulnerable porcelain component of the equipment alone can be tested when the whole equipment can not be experimentally qualified using shake table due to payload limitation of the test setup. Since accelerometers were mounted on top of the insulator assembly, amplification factor at the base of the insulator could not be determined experimentally. The adequacy of the finite element modelling is demonstrated by comparing the analysis results and shake table results, as they match very closely.

From the Finite element analysis, the relation ship between amplification factor and the vibration frequency at the top and base of the porcelain insulator assembly along X-axis and Y-axis were obtained and shown in Figures 3–6 respectively.

From these graphs, the amplification factor along X-axis and Y-axis corresponding to the first mode, one having higher mass participation factor in the respective axis is obtained as 2.5 along X-axis and 1.5 along Y-axis.

For seismic qualification using shake table tests, Standard IEEE 693-2005 recommends an amplification factor of 2.5 for both the axes. Finite element analysis prior to shake table tests was preferable to evaluate precise amplification factor for seismic qualifications.

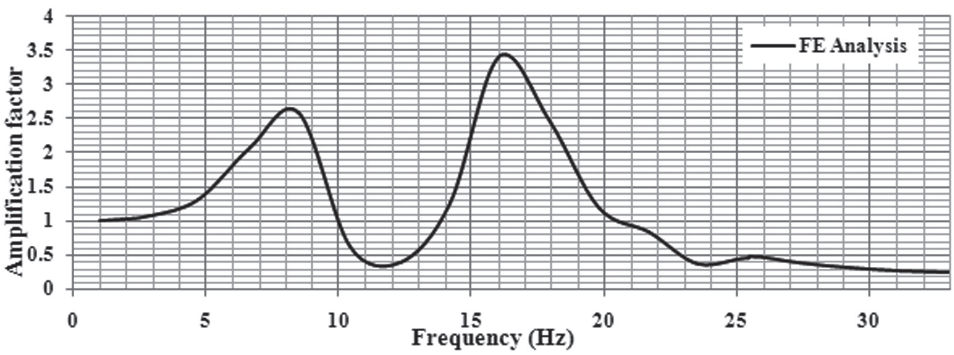

FIG. 5 RESPONSE AMPLIFICATION AT THE BASE OF THE PORCELAIN INSULATOR OF 12 kV CIRCUIT BREAKER IN X-AXIS.

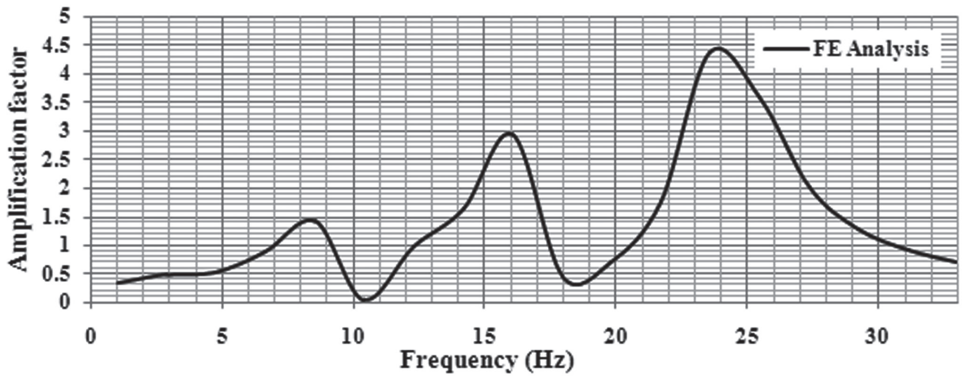

FIG. 6 RESPONSE AMPLIFICATION AT THE BASE OF THE PORCELAIN INSULATOR OF 12 kV CIRCUIT BREAKER IN Y-AXIS.

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REFERENCES

[1] Carmona J S, Zabala F, Santalucia J and Sisterna C. "Seismic tests of high voltage equipment in argentine" *Earthquake Engineering 10th World Conference*, 1992.

[2] Chandrasekaran A R and Singhal N C. "Earthquake resistance capability of voltage transformer", *Journal of Energy Engineering*, Vol. 110, pp. 18641, 1984.

[3] Hatami M, Ghafory M and Hosseni M. "Experimental and analytical study of a high voltage - instrument transformer", *13th World Conference on Earthquake Engineering*, pp. 2550, 2004.

[4] Keum Y T, Kim J H and Ghoo B Y. "Computer aided design of electric insulator", *Journal of Ceramic Processing Research*. Vol. 1, No. 1, pp. 74–79, 2000.

[5] Stefanov D. "Analytical and experimental seismic qualification of 3 types of electric transformers" *Transactions*, *SMiRT*, August 2007.