BEHAVIOUR OF A 220 KV TRANSFORMER UNDER SIMULATED EARTHQUAKE CONDITIONS

A.R. Chandrasekaran (I)
N.C. Singhal (II)
Presenting Author : A.R. Chandrasekaran

SUMMARY

A 220 KV Voltage Transformer is theoretically analysed and experimentally tested under simulated earthquake conditions. A new criterion is suggested based on dynamic response of the system during a postulated design earthquake to assess the earthquake withstand capability of the system due to different support mountings. Shaking table tests are carried out to simulate the above response. A new scheme is suggested to simulate the dynamic loading by an equivalent static loading.

1. INTRODUCTION

The damage to power station equipment due to earthquakes has now necessitated the need for a detailed study of dynamic behaviour of electrical systems. The earthquake performance of such systems has become important as their malfunction or damage can cause a lot of dislocation of life of a community besides other economic losses. For instance, at the time of Koyna (India) earthquake of Dec. 11, 1967, eventhough there was no damage to the city of Bombay (nearly 200 kms. away) industrial production was affected due to disruption in power supply.

In case of equipment, particularly those of power plants which are now considered to be a part of life-line systems, they are expected to remain functional even after the severest earthquake at the site. Thus there is a necessity to estimate the most credible earthquake for the site.

The support mountings of these equipment play an important role as it changes the dynamic characteristics of the equipment. In India, the manufacturers of the main electrical equipment have no direct responsibility for the design of the support mounting (as it is done by a different agency) and support details are not known a priori. The equipment should, therefore, be tested in the laboratory for a response which may cater for different types of support mountings eventhough the manufacturers are asked to certify for an earthquake time-history/spectra at the base of the equipment.

This paper deals with theoretical and experimental studies of dynamic behaviour of one such electrical equipment, namely, 220 KV Voltage Transformer (V.T.). This is a cascade electromagnetic type transformer used for measuring the line voltage and consists of top chamber assembly, porcelain insulator which houses the primary and secondary windings, and the base assembly (Fig. 1).

(I) Professor
(II) Lecturer
Department of Earthquake Engineering, University of Roorkee, Roorkee - 247667, INDIA.

The porcelain insulator is the most delicate and important part which is not supposed to sustain even hair cracks. The properties of the porcelain have been obtained from free vibration test as well as static lateral load test. Dynamic analysis of the V.T. has been carried out by two methods. In one, it is analysed as an assemblage of beam elements and instead of the actual shape of the petticoat an equivalent shape has been assumed. In the second, axisymmetric finite element analysis has been done wherein actual shape of the petticoat has been preserved. The results of these two types of analysis have been compared.

The techniques of earthquake withstand tests of full scale prototype equipment as suggested by Novoa (Ref. 1), IEEE (Ref. 2) and IEC (Ref. 3) do not fully reflect the actual behaviour of such equipment during earthquake. A new criterion of earthquake withstand tests has been evolved based on realistic dynamic response during a postulated design earthquake rather than adopting an arbitrary specified percentage of acceleration due to gravity to be applied at the base sinusoidally. The proposed method takes into account the response of the equipment due to postulated earthquake and the flexibility introduced due to support mounting.

2. SIMULATED EARTHQUAKE

Ground motion can be indirectly represented in the form of response of idealized linear single degree-of-freedom system to a ground motion, known as response spectra. Normalized shapes of response spectra are now available for different soil conditions as well as confidence levels. Fig. (2) gives one such shape of acceleration response spectra. It has a steep rise from the zero period acceleration value (ZPA) to a maximum value in a short period range from 0.0 to 0.1 sec, a flat shape in the period range of 0.1 sec to 0.4 sec with an amplification of 2.5, and thereafter it gradually decreases slowly to 1/5th of the maximum value. Thus once the shape of spectra is chosen, only a constant multiplying factor (usually in the form of ZPA value) would decide the design spectra. In the present study, ZPA has been taken as 0.3 g and this spectra corresponds to maximum credible earthquake conditions for the most severe site envisaged for the installation of the equipment.

These equipment are normally mounted in switchyards on supports. These support mountings change the dynamic characteristics of the equipment. The combined system would become flexible. The period of the combined system may shift to the right of the flat range of spectra and spectral acceleration (Sa) would decrease. However, if the equipment is too stiff such that its period (assumed fixed at the base) lies to the left of flat range, then with flexible mounting the period may lie in the flat region itself causing an increase of Sa rather than a decrease.

This equipment response during an earthquake is mainly in the first mode. If the acceleration response is the criterion to be achieved for any type of base mounting, and if Sa in the first mode is assumed to have a value corresponding to flat region (0.75g in the present example), irrespective of value of fundamental period, then the design would be achieved as the mode participation factor is nearly the same for various cases. Incidentally, if the same mounting is used for qualification test as well as in the field, then other response parameters like displacement, bending moment and shear would also be satisfied. However, if the mounting is different in the two cases, with the field one being more flexible, then eventhough acceleration response may be satisfied, other quantities like moment, etc., may not be achieved. It may be necessary to carry out analytical parametric study to evaluate the bending moment and shear response. The experimental set-up should be such as to achieve the maximum value of moment and shear response by suitably scaling the acceleration response.

In the present case, at the time of qualification the target spectra was specified for fixed base condition. The field tests were carried out much later and the paper examines whether the qualification would also satisfy field mounted condition.

3. FREE VIBRATION TESTS

Free vibration tests were performed on the V.T. fixed at the base in the laboratory and with mounting in the field on a typical installation. Such tests were carried out by gently pulling the V.T. at the top by a rope and then suddenly releasing it, thus causing the V.T. to perform free vibrations about its static equilibrium position. The amount of pull was such that the initial displacement remained in the elastic range.

From the free vibration tests of the V.T., the fundamental frequencies without and with mounting were observed to be, respectively, 13Hz and 1.4Hz. This is a substantial alteration in the dynamic behaviour of the V.T. The corresponding values of damping were found to be 2.5% and 1.0%. However, in the case of earthquake excitation, the amplitude of vibration would be much larger and corresponding damping would also increase. A nominal value of 5% critical damping was, therefore, assumed in the analysis.

4. THEORETICAL ANALYSIS

Theoretical analysis was done to evaluate the peak response acceleration and the stresses in the system. Two types of analysis-beam and axisymmetric finite element - were performed for a typical Voltage Transformer shown in Fig. (1) for the cases without and with mounting.

4.1 Beam Analysis

The V.T. was treated as an assemblage of beam elements. An equivalent shape of the petticoat was assumed instead of actual shape as shown in Fig.(2). Beam element is a 2-noded element with translational and rotational degrees of freedom per node. The deformations due to bending and shear and the effect of rotatory inertia have been included.

4.2 Axisymmetric Finite Element Analysis.

The V.T. is an axisymmetric structure except for the base support assembly made of steel and square in plan. The base assembly portion has been assumed to be an equivalent axisymmetric hollow cylinder of same moment of inertia. The actual shape of the petticoats was preserved by modelling them by 8-noded parabolic elements. Elsewhere, the 6-noded paralinear elements were used. An harmonic analysis was done employing Fourier series whereby a 3-D analysis becomes equivalent to superposition of a series of 2-D analyses (Ref. 4).

4.3 Results

4.3.1. Frequencies and Mode Participation Factors

Table 1 shows the frequencies and mode participation factors for the first three modes of vibration of the V.T. without and with support mounting using the above two types of analysis. It is observed that both the analyses give comparable results. Also, the theoretical fundamental frequency in horizontal direction in both the cases matches well with the corresponding experimental frequency. The fundamental frequency reduces drastically with the mounting of support. In the vertical direction, even the fundamental frequency is very large indicating that the system is quite stiff in the vertical direction and could be treated as a rigid body in this direction.

4.3.2. Stresses

The moments and shears under static and dynamic conditions can be related as below:

$$M_{dyn} = Cm\ W\ \bar{H}\ Sa^{(1)}/g\ , \quad V_{dyn} = Cv\ W\ \ Sa^{(1)}/g$$

where M_{dyn} = dynamic moment, V_{dyn} = dynamic shear, W = weight of V.T. only, $\bar{H}$ = height of centre of gravity of V.T. alone above its base, $Sa^{(1)}$= Spectral acceleration in the first mode, and Cm and Cv are nondimensional constants.

Since the first mode of vibration contributes the major share of the total response, the total response is expressed in terms of Sa in the first mode. The values of Cm and Cv are as follows:

(i) Case A: Without Support Mounting	(ii) Case B : With Support Mounting
Cm = 0.840, Cv = 0.575	Cm = 1.118, Cv = 0.991

It could be noted that the constants Cm and Cv are larger when V.T. is on a flexible mounting, for the same Sa value. However, with the longer period of the flexible support the Sa value also decreases.

Substituting the value of $Sa^{(1)}$ in the two cases (assuming $Sa^{(1)}$ in Case A to be 0.75g eventhough the value for 13 Hz is smaller, and in Case B corresponding to 1.4 Hz):

M_A = 105905 kg cm $\quad V_A$ = 517 kg

M_B = 78835 kg cm $\quad V_B$ = 500 kg

where M and V stand for dynamic moment and shear, respectively.

It can be seen that the actual moment and shear in case of flexible mounting are lesser in this case. The maximum vertical tensile stresses at the base of porcelain for the Cases A and B are respectively, 13 kg/cm^2 and 9 kg/cm^2. The corresponding compressive stresses are - 16 kg/cm^2 and -13 kg/cm^2. The shear stress in both the cases is very small, about 1.5 kg/cm^2. The value of ultimate tensile stress in porcelain is specified as 100 kg/cm^2. Thus the stresses developed in porcelain are within permissible limit.

5. FORCED VIBRATION TEST

For testing such equipment to withstand earthquakes, it would be ideal if the testing is done on a shaking table which could be given the same motion as that of the postulated earthquake. Alternatively, the equipment can be analysed for maximum response at criterial location of the equipment (in this case moment and shear at the base) and then subjecting the equipment to a base motion so as to achieve the above response at this location.

5.1 Design Motion for the Shake Table

The response acceleration at the top of equipment for case A without mounting is 1.13g. To satisfy the dynamic moment/shear under flexible condition of mounting, the response acceleration at the top of equipment would be $1.13 \times 500/517 = 1.10g$, as the base shear governs the design in this case.

The shaking table was given such a sinusoidal base motion that at resonance of the equipment, the desired acceleration response was achieved at the top of the equipment. Since the response is mainly in the fundamental mode and the mode shape remains nearly the same for different mountings, the design criteria for various parameters would be satisfied.

The equipment was subjected to a vibration environment giving 1.20g response acceleration at its top during resonance.

5.2 Testing Arrangement

Forced vibration test in horizontal direction was done by mounting the V.T. on a shaking table. The shaking table used had a dimension of 3.66m x 1.83m and was supported at 6 points on spherical ball supports which moved on a V-groove. The table was driven by two types of mechanical drives both of which generate sinusoidal type motion. They were (i) double eccentric cam device (a displacement controlled device) which is suitable for low frequency excitation, say 1 Hz to 12 Hz, and (ii) a mechanical oscillator (a force controlled device) having two eccentric masses rotating in opposite directions and which can be used for high frequency excitation, say, 12 Hz to 33 Hz.

The vibrations were sensed by accelerometers. The signals from the accelerometers were fed to amplifiers and from amplifiers to an ink-writing oscillographs which produced permanent and immediately readable records of the motion.

6. STATIC LATERAL LOAD TEST

An alternate but indirect method to qualify such equipment to withstand the postulated earthquake may be to test them in static condition by applying loads laterally. During an earthquake various parts of a structure move differently with respect to its foundation and these relative deformations cause strains and stresses in the system. If the dynamic deflection curve could be predicted, it may be possible in an ideal experimental set-up to simulate the dynamic deflection pattern by application of external static loads along the height of the structure. However, in practice for simulation of horizontal excitation, a lateral force is specified to be applied at the top of the structure and deflections and strains measured at various locations along the height.

To simulate the dynamic behaviour, the lateral static loads should be so applied as to envelop the theoretically evaluated dynamic shear force and bending moment distribution along the height. Theoretical analysis could be used to predict the dynamic shear forces and bending moments at various locations along the height of the structure. One way to achieve this would be to apply a single concentrated load at the top of the equipment. The static shear force diagram in this case would be a rectangle and bending moment diagram would be a triangle. This would represent rather a severe condition at most levels as the values must match at the base. However, a better simulation would be to apply a series of concentrated loads at different locations along the height of equipment so as to envelop the dynamic shear and moment diagrams. Fig. (3) shows these shear and moment diagrams and the proposed distribution to be obtained by equivalent static loads.

In the present case, a single lateral load of 43% of weight of equipment applied at the top would envelop the dynamic shear diagram and similarly 30% of weight would envelop the dynamic moment diagram. The corresponding values in case of flexible mounting are 41.7% and 22%, respectively.

7. CONCLUSIONS

Design criterion has been suggested based on dynamic response of the system during a postulated design earthquake to assess the earthquake withstand capability of a Voltage Transformer. The criterion uses a theoretical cum-experimental approach. The experimental results of natural frequency and damping are utilized to evaluate theoretically the maximum response which would be expected to occur at various locations of the equipment. To determine the response, the peak response acceleration of the spectra is used to accommodate the uncertainties because of the system being flexible when supported on different mountings. For testing the equipment, it is mounted on a shaking table which is given a base motion such that the theoretically evaluated response is achieved in the forced vibration test. A new proposal is suggested to simulate the dynamic loading by lateral static loading in a rational manner.

In the present study, the fundamental frequency obtained analytically matches well with that obtained experimentally. The results from beam and axisymmetric finite element analyses compare well. Analytical results predict that the voltage transformer when subjected to specified earthquake environment would have stresses within permissible limits. Experimentally, the transformer withstood the forces generated during dynamic tests for the simulated design earthquake environment for the initially assumed rigid base mounting as well as the actual field mounted condition.

ACKNOWLEDGEMENT

The study for the case of rigid base mounting was sponsored by Bharat Heavy Electricals Limited, Jhansi (U.P.), India.

TABLE 1 - FREQUENCIES (f) IN Hz AND MODE PARTICIPATION FACTORS (Cr)

(a) V.T. WITHOUT SUPPORT MOUNTING, i.e., HELD AT ITS BASE

MODE	BEAM ANALYSIS				AXISYMMETRIC ANALYSIS			
	Horiz. vibration		Vert. vibration		Horiz. vibration		Vert. vibration	
	f	Cr	f	Cr	f	Cr	f	Cr
1	12.98	1.50	88.33	1.27	13.83	1.50	94.29	1.24
2	67.74	0.73	270.70	0.40	66.68	0.76	287.82	0.46
3	155.65	0.39	422.07	0.21	153.27	0.46	439.00	0.21

(b) V.T. WITH SUPPORT MOUNTING, i.e., HELD AT BASE OF MOUNTING

MODE	BEAM ANALYSIS				AXISYMMETRIC ANALYSIS			
	Horiz. vibration		Vert. vibration		Horiz. vibration		Vert. vibration	
	f	Cr	f	Cr	f	Cr	f	Cr
1	1.39	1.35	70.92	1.20	1.52	1.36	68.12	1.22
2	14.19	0.55	240.45	0.30	13.78	0.53	221.86	0.31
3	45.66	0.46	417.79	0.21	45.82	0.45	399.41	0.23

NOTE : Experimental frequencies in horizontal direction without and with support mounting were 13 Hz and 1.4 Hz, respectively.

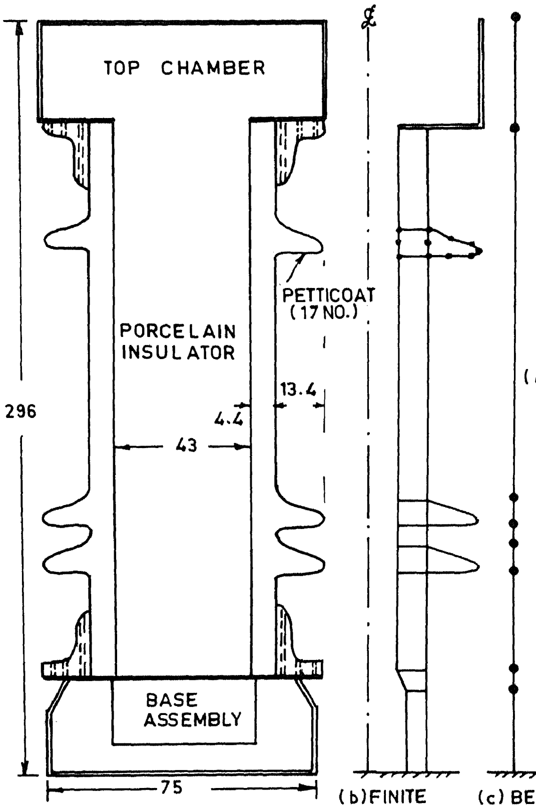
REFERENCES

1. Novoa, F., "Earthquakes and the Substation Equipment Arrangement and Specifications", CIGRE Paper 23-02, International Conference on Large High Tension Electric Systems, Paris, 1970.

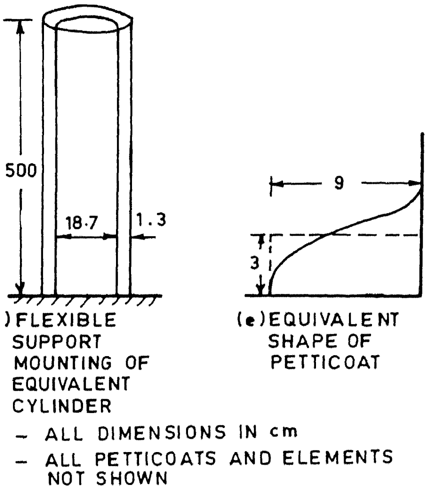
2. IEE Std 344-1975, "IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations", Institute of Elect. and Electronics Engineers, Jan. 1975.

3. International Electrotechnical Commission, Document 50A (Secretariate) 192, July 1982.

4. Zienkiewicz, O.C., "The Finite Element Method", 3rd Edition, McGraw-Hill, 1977.



(a) VOLTAGE TRANSFORMER (b) FINITE ELEMENT IDEALIZATION (c) BEAM IDEALIZATION



(d) FLEXIBLE SUPPORT MOUNTING OF EQUIVALENT CYLINDER

(e) EQUIVALENT SHAPE OF PETTICOAT

- ALL DIMENSIONS IN cm
- ALL PETTICOATS AND ELEMENTS NOT SHOWN

FIG.1 _ VOLTAGE TRANSFORMER AND ITS IDEALIZATION

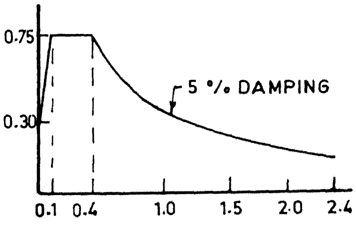


FIG.2 _ NORMALIZED SHAPE OF ACC. SPECTRA

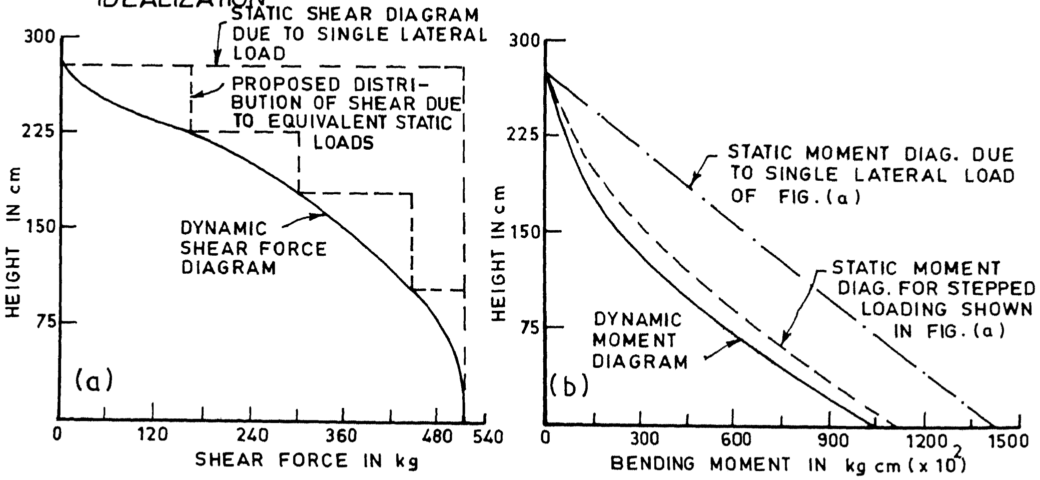


FIG. 3 _ SHEAR FORCE AND BENDING MOMENT DIAGRAMS