Earthquake resistant design of a transformer

A. D. Shendge
Technology Department, Transformer Division,
Crompton Greaves Ltd, India

Abstract

The safety of the transformer and the environment around the plant should be ensured against all natural hazards including earthquakes. With public safety as the paramount concern, the transformer is designed to withstand low probability high magnitude earthquakes. This paper deals with seismic design aspects of a 50MVA, 110KV power transformer such as the ground motion generation, seismic analysis and earthquake qualification, etc. The finite element analysis tool has been used to carry out modal analysis and spectrum (mode combination) analysis. Spectral analysis is used to combine the effect of the structure's modes on one of the equipment modes and, also, combine the effect of equipment modes with respect to stresses or displacements in the equipment modes of the structure
Keywords: earthquake, transformer, seismic design, dynamic analysis, response spectrum, and finite element analysis.

1 Introduction

A transformer consists of various structures, which are designed to resist earthquake forces. Earthquake is a natural phenomenon, which is generated in earth crust in the form of seismic waves, generating ground vibrations travelling far and wide and gets attenuated as they travel. Such ground vibrations or base motion at the base of the transformer [Fig.1] gets transmitted through the under base of the transformer to the structure such as core, coil, conservator, radiator, bushing and tank mounted lightning arrestor. The earthquake motion mainly induces inertial forces in the structure. The Transformer structure is designed to resist these earthquake forces along with other loads, viz. Gravity, pressure, wind load pull and thermal loads etc. The detailed seismic requirement [1] for each component, including whether it is required to operate after an earthquake, or

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during and after an earthquake are identified and the components are designed accordingly.

2 Transformer

Transformer tank is filled with transformer oil. The primary driving force causing the tank to fail is due to seismic response of transformer oil and core coil. While calculating the response of the oil inside the tank and its horizontal ground motion, one has to consider the two response modes of the tank and its contents.

The transformer tank is secured to the foundation by friction. For such tanks, major damages may occur because of sliding or overturning. For seismic resistance, these tanks are secured to the foundation by providing anchoring with the bolt. These bolts should be designed for the earthquake resultant forces, otherwise the bolt threads can get damaged or the bolt can get uprooted.

2.1 Earthquake strength problems of transformer

According to literature data and results of investigations, failures of the transformers owing to earthquakes can be divided in to four groups [2].

a). Failure connected with the transformer moving from the site. (Roller rim damage, carriage damage or deformation, tank bottom failure as the result of falling form carriage on rail foundation, LV bushing failure, conservator brackets deformation)

b). Failure connected with core-coil shifting inside the tank. (Deformation or breakage of centring elements and stops with insulation gaskets fallout, winding taps deformation, and destruction of bushing lower porcelain covers, changing of insulation gaps to the earthen constructions)

c). Failure connected with the destruction of HV bushing outer porcelain covers (damages of bushings, transformer unsealing, leakage's of some volume of oil)

d). Failure connected with complete unit's failure (Switching off because of false protection operation)

2.1.1 Seismic design approach for transformer

The judgement applied in evaluating the extent to which the seismic mitigation measures to resist the earthquake should be implemented. Design of the structure is based on the expected acceleration and frequency content of the earthquake. For seismic study, ultimately actual data are used, to some extent, these studies are subjective and judgment, experience and common sense set the criteria, approach and procedures for seismic design. The levels of importance of the structure are established and seismically designed. While covering the global qualification of the system, it is required that the support structure, conservator, tank, bushing, lightning arrestor, radiator, cable box, core and coil are seismically qualified.

Based on the performance of the structure during the past earthquakes and the lessons learnt from them, engineering solutions have been sought to mitigate the earthquake- induced damages to the equipment. The present seismic design procedures adopted in the design are covered in the subsequent discussion.

2.2 Seismic standards

IEEE document #344-1987 [3] specifies acceptable methods for qualifying equipment and includes seismic analysis and test method. The seismic level that must be met is usually expressed in terms of two magnitude of earthquake- the "Operating Basis Earthquake " and the " Design basis earthquake".
The design basis earthquake is usually considered to produce accelerating force 1.8 times [4] as great as the OBE, and this is the basis of the intensity multiplier used.

2.2.1 Seismic design of transformer

The following parameters are considered for design of transformer
1]. Portion of the liquid slashes back and forth across the transformer tank and has a low frequency of oscillation.
2]. The bending moment generated on the tank shell induces compressive stresses on the tank and is maximum, at the bottom of the tank
3]. Under base of the tank is designed to prevent uplift of the tank due to rocking.
4]. Expansion anchor bolts are used to clamp the tank to the foundation
5]. Full penetration welds on both sides of the shell welded to the bottom plate and radiographic or x-ray inspection of the weld to be performed.
6]. Abrupt changes in the thickness of the shell wall shall be eliminated.
7]. For seismic resistance, transformer has to be rigidly mounted to the floor and designed for seismic forces.

3 Static method

For design and verification, the seismic intensity of an area is characterized by means of the parametric a, v, and d that represent the absolute values of the acceleration, speed and horizontal displacement in the surface of the land. When they are not defined, the standard parameters of the horizontal movement[5] will be the following ones.

Horizontal acceleration (a) = 0.50 g v = 50cm/sec d = 25cm

The horizontal force of seismic design applied on horizontal plane in which the seismic action is applied, it will be given by:
[A]. Rigid equipment with natural frequency higher than 30 Hz.

Horizontal seismic force = 0.5 *W

W = sum of the weight located on the horizontal pane of application of the seismic force.

Vertical seismic force = 0.25*W

[B]. Equipment with natural frequency lower than 30 Hz

Horizontal seismic force = 1.2 A W/ (R*g)

Assume R = Coefficient of modification of the response = 3

Vertical seismic force = 0.6 A W / (R*g)

This horizontal force acts at center of gravity of transformer in horizontal direction. The most vulnerable case is seismic force acting perpendicular to transformer length.

In order to estimate stress applied to an anchor bolt, a simple static method is used. Fig.1 shows the earthquake force statically applied to the center of gravity of a transformer to the anchor bolt. Tensile and shear stress should not exceed the limiting value of the anchoring bolt. Stress calculation and force calculation are given in appendix I, which are less than 2500 kg/cm^2

Location of bolts along longitudinal and lateral directions is as shown in fig. 3.

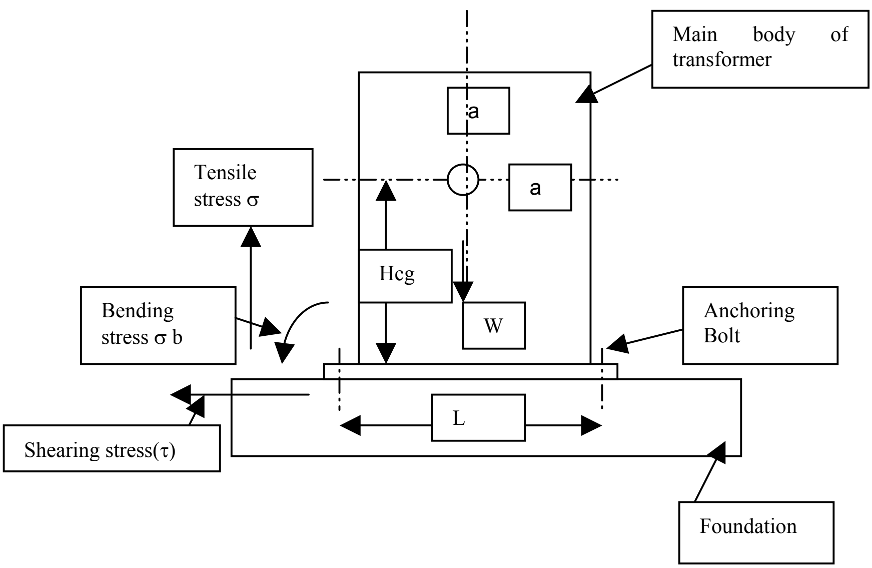

Figure 1: Anchoring bolt stresses by earthquake.

4 Natural frequency of transformer

The static method will be applied to rigid equipment that forms an independent unit mounted in unique foundation in the floor without a support structure.

Equation of motion: Consider the small oscillation of mathematical model in fig 4 the degree of freedom are identified as x and θ.
The equation of motion are written as follows

$$\Sigma V = 0$$

$$W (d^2X/dt^2 + L_1 d^2 \theta /dt^2) + k_1 x + k_2 (x + L \theta) = 0 \quad (1)$$

$$\Sigma M = 0$$

$$W (d^2X/dt^2 + L_1 d^2 \theta /dt^2) L_1 + k_2 (x + L \theta) L + J d^2 \theta /dt^2 = 0 \quad (2)$$

From fig. 4 polar moment of inertia of transformer support structure is given by Jxx = (B*H^3 –b*h^3) / 12.

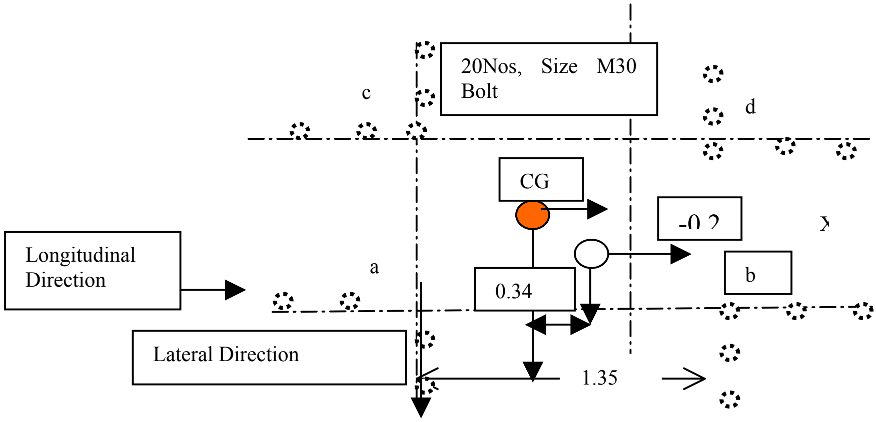

Figure 2: Location of anchoring.

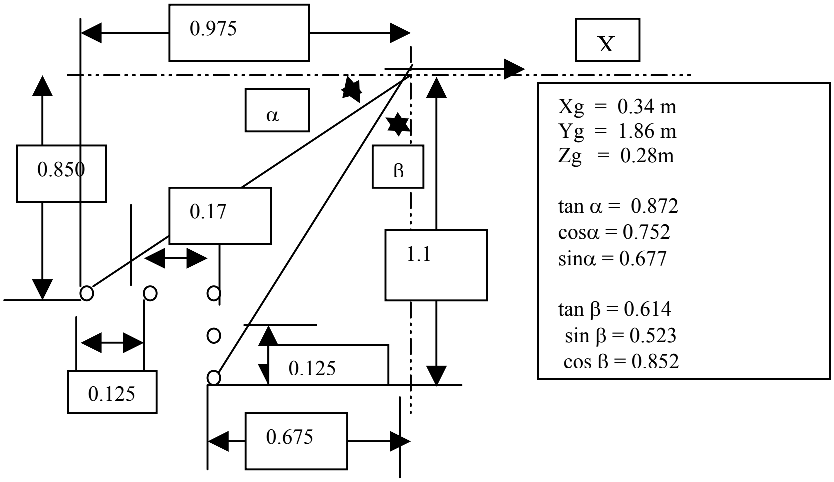

Figure 3: Resolving forces at quarter part of the foundation bolt.

Jxx = Polar moment of inertia
E= 2.1* 10^{6} kg/cm^2
where C= 9.82 (2^0 Mode of vibration)

Solving equation (1) and (2) we have, Natural frequency (f_n)

$$f_n = C\sqrt{\frac{EJg}{WL^3}} = 74Hz \tag{3}$$

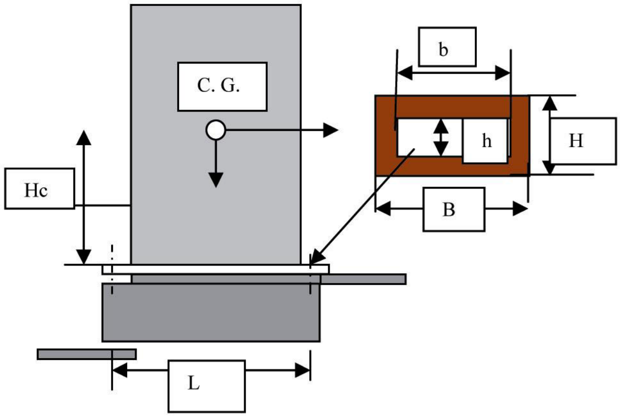

Figure 4: Configuration of transformer.

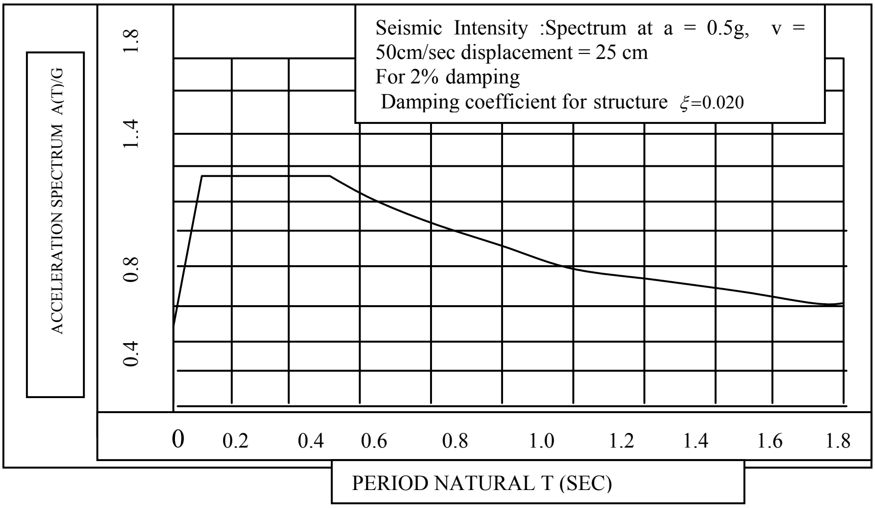

Figure 5: Typical design response spectrum for 2 % damping.

5 Dynamic analysis

An earthquake causes an alternating ground motion, which varies with time and is harmful mainly because of the acceleration and thereby, the inertial forces induced in the structure. Seismic input motion is generally recorded and represented by an accelerogram also called as "Time History". Earthquake motion is cyclic random motion, containing a mix of frequencies. The maximum acceleration of the ground motion is the peak acceleration of the time history plot. A typical acceleration spectrum A(T) /G vs. Natural period T (sec) [6] is given in fig. 5.

5.1 Response spectrum

The time history plot does not directly provide perceptible information to the design engineer. The harmfulness of acceleration and the forces induced in the structure to a given seismic excitation is predominantly due to the classic resonance phenomenon, or dynamic amplification. We know that if the excitation frequency is close to the natural frequency of the structure, the response of the structure is dynamically amplified and is a function of damping of the structure. The frequency content of the time history and the effect of damping, essential for the understanding of dynamic amplification of the structure during an earthquake are expressed usually by a concept of "Response spectrum "

The characteristics of an earthquake are such that it is relatively rich in energy content in the frequency range of 1 to 15 Hz. above 15 Hz; the energy content reduces considerably and is very less beyond 33 Hz. The peak acceleration of the time history plot corresponds to the acceleration value of the response spectrum plot at 33 Hz and is called as **Zero Period Acceleration (ZPA)**

5.2 Finite element analysis using response spectrum

Let us see the seismic force calculation for a tank. This tank can be idealized as a single degree of freedom oscillator with stiffness of the tank & support and mass of tank. The damping of such equipment is say 2%. Now, by using horizontal floor response spectrum of the floor for a 2 % damping, the acceleration experienced by tank mass at frequency is 0.5 g. The tank will thus experience a horizontal force proportional to this acceleration. Similarly, seismic forces in other orthogonal horizontal and vertical direction are calculated by static method. If the natural frequency of structure is below 33 Hz or the earthquake-induced forces would either strengthen the support structure or increase its natural frequency above 33 Hz or shift the tank to a lower elevation. The tank support and its anchor bolts are then designed for these calculated seismic forces in combination with dead weight & pressure.

Finite element analysis tool is used to carry out response analysis for the transformer as per norm mentioned in specifications.

Following steps are used to find out the natural frequency and maximum stress on the structure after applying seismic condition.

1]. Modal analysis used to find transformer natural frequencies and mode shapes

2]. Spectral analysis used to combine the effect of the structure's modes on one of the equipment modes and, second, combine the effect of equipment modes with respect to stresses or displacements in the equipment Modes of structure. However results apply to any modes of the two systems, i.e. the response of any mode of the equipment associated with any mode of the structure may be determined.

To develop dynamic procedures, several existing finite element codes were considered to avoid reinventing and writing several meshing and other analysis codes. Ansys was found to be most suitable to accomplish this task. Here, the solid model of the transformer as shown in fig. 6 is constructed using ansys and meshing of it is constructed by 10-node tetrahedron element. The core coil is constructed using 3-D beam element. A natural frequency of transformer is as shown in fig. 7.

Table 1: Transformer natural frequency.

Sr. No.	Calculated	FEA	% deviation
01	74	72.34	2.24
02	-	113	-
03	-	531	-

The computer FE model described above has been compared with the corresponding computed data. Table 1 gives good agreement between finite element analysis and calculated values validate the developed FE model.

6 Conclusion

In this paper, a new scheme based on finite element method has been developed for earthquake resistant design of power transformer. The performance criteria for the transformer are defined before the design stage based on its function. The transformers are seismically qualified using state of the art techniques involving both seismic analyses to ensure that the transformer is capable of safety surviving an earthquake. Earthquake resistant ground motion generated to avoid shear of foundation bolt.

Various international codes like ASME, IEEE, ANSI, ENDESA etc. are used in the seismic design of transformer.

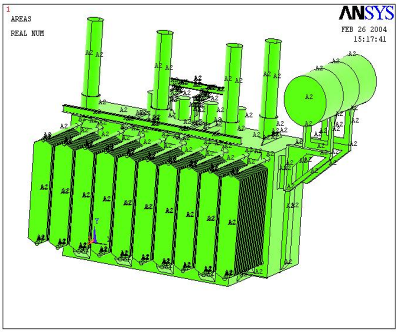

Figure 6: Solid modelling of transformer.

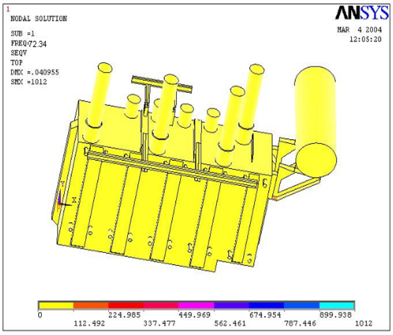

Figure 7: First modes of transformer.

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Appendix I

The following symbols are used in this paper:

E	=	Modulus of Elasticity
fn	=	Natural frequency
I	=	Moment of Inertia
J	=	Polar moment of Inertia
k	=	Structural Stiffness
L	=	Member length
M	=	Bending Moment
W	=	Weight of Transformer
x,y,z	=	Global co-ordinate axis
X_g, Y_g, Z_g	=	Global Co-ordinate for Centre of gravity
Z	=	Section modulus
a_h	=	Horizontal Acceleration
a_v	=	Vertical Acceleration
ξ	=	Damping Coefficient
θ	=	Joint rotation about subscript axes
α	=	Angle With horizontal axis
β	=	Angle with vertical axis
τ	=	Shear stress
σ	=	Normal stress
σ_1	=	Maximum stress along longitudinal direction
σ_2	=	Maximum stress along lateral direction

Appendix II

Description of foundation bolt stress calculation: Stresses developed in the foundation bolt along longitudinal and lateral direction can be calculated as follows, and direction of forces are shown in the fig. 2 & fig. 3

Moment of inertia of bolt is given by

$Ixx = 1223900.cm^4$

$Z^1xx = Ixx/ 85 = 14399\ cm^3$ $Z^2 xx = Ixx / 110 = 11126\ cm^3$

$Izz = 859670.cm^4$

$Z^1zz = Izz/ 97.5 = 8817\ cm^3$ $Z^2 zz = Izz / 67.5 = 12736\ cm^3$

Total Moment of inertia of bolt is given by

$Ip = Ixx + Izz = 2083570\ cm^4$ $Z^1p = (Ip/ 97.5) \cos\alpha = 16113\ cm^3$

$Z^2 p = (Ip / 67.5) \cos\beta = 16138\ cm^3$

1] Seismic force along + x & -y direction:

Total vertical force Fy = -125 + 31.75 = -93.75T

Horizontal seismic force Fx = 62.5 T

Fz = 0 ; Mx = - Fy * Zg = 26.25 T-m, My = Fx*Zg = 17.5 T-m

Mz = - Fx * Yg + Fy * Xg = - 111.875T-m

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a] Stresses on bolt along longitudinal direction

$\sigma = (Mx/ Z^1xx + Mz/ Z^1zz) – Fy / (n^* A)$ = 788 kg/cm^2

$$\sigma_1 = \sqrt{\frac{Fx}{n * A} + \frac{My * \sin\alpha}{Z^1 p})^2 + (\frac{My * \cos\alpha}{Z^1 p})^2}$$

σ1 = 520 kg/ cm^2

b] Stresses on bolt along lateral direction

$\sigma = (Mx/ Z^2xx + Mz/ Z^2zz) – Fy / (n^* A)$ = 451 kg/cm^2

$$\sigma_2 = \sqrt{(\frac{Fx}{n * A} + \frac{Mx * \sin\beta}{Z^1 p})^2 + (\frac{Mx * \cos\beta}{Z^1 p})^2}$$

σ_2 = 538 kg/cm

Similarly, seismic force along - x and –y direction has been checked.

The Capacity of bolt is much higher than yield stress. Therefore, design of transformer is ok.

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