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Robert Platek
ABB Sp. z o.o. Corporate Research, Poland
robert.platek@pl.abb.com

Grzegorz Juszkiewicz
ABB Sp. z o.o. Corporate Research, Poland
grzegorz.juszkiewicz@pl.abb.com

SEISMIC ANALYSES FOR POWER TRANSFORMERS

SUMMARY

Reliability and security of power systems, especially in areas prone to earthquakes, depends on the seismic withstand of its components and interaction of these components with other elements. All relevant power products and components should be designed and tested to guarantee high seismic performance. Option which is strongly recommended for seismic qualification is shake table test. This way is very expensive and in some cases like power transformers impossible due to its weight and size. Because of this the numerical analyses can be very helpful to determine the dynamic characteristic of the system. This way is more and more used during evaluation of seismic performance of power products, especially in the design phase.

In the paper a different numerical approaches for seismic analyses of the power transformers have been presented. In the first part of the article focus was put on typical simulation methods defined by IEEE and IEC standards. This approach is dedicated only for transformer's components. Due to fact that standards do not provide clear information about fluid influence on power equipment during seismic events, some investigations related with oil filled transformers were done and summarized. Three different numerical methods were investigated. First one is built based on the Fluid-Structure Interaction (FSI) methodology. In this approach combination of different software (CFD, structural, and coupling code) is used to cover phonemes related with fluid dynamics and structural analyses. FSI methodology gives a wide possibility but, it's very complex however, is very complex which can be a disadvantage for very complex objects. Next one uses acoustic elements, where the fluid is modeled as acoustic medium. This is method which allows to take into account fluid during seismic simulations in simplified way. The last one uses Lagrange and Euler element formulations (CEL) in which sloshing effect of the oil in power products can be considered. All this approaches can be very helpful to determine the dynamic characteristic of the transformers and its equipment including fluid.

Key words: transformer, seismic, Finite Element Method (FEM), acoustic medium, Fluid-Structure Interaction (FSI), Coupled Euler – Lagrange (CEL)

1. INTRODUCTION

1.1. Seismic Performance Overview

Seismic forces with which we meet mostly during the earthquake is a natural phenomenon arising in the Earth's crust in the form of seismic waves, generating low frequency vibrations and weakening during propagation. Seismic loads are some of the dynamic loads which may affect not only the buildings, but also in power devices. Power transformers are one of the critical components in power systems. Their reliability and safety exposed to earthquake loading is dependent upon the seismic response of its selected components and interaction of these components with other elements. As a result, all relevant power products and components, operating in seismically active areas, should be designed and tested to guarantee high seismic performance.

The standards indicate that the seismic qualifications should be done for critical elements (bushings, conserver system) of transformer by shake table testing. It is acknowledged that the supporting structure of the bushing or conserver (tank, top plate, etc.) amplifies the ground acceleration. The latest studies indicate that the dynamic response of bushings mounted on transformer tank is greatly different than to the rigid frame used in standards testing. Its dynamic characteristics are influenced by flexibility of the top plate of the transformer tank [1, 2]. Another issue is fluid, that exists in such product like transformer. Standards does not provide clear information about fluid influence on the supporting structure of bushings and changing dynamic characteristic under seismic loads.

Making power products earthquake-proof is no easy task. However, many years of ABB experience in this field helped to understand nature of seismic events. Efficient analyses of seismic loads based on the standards go far towards to develop innovative approaches to this type of problems.

1.2. Standards for Power Transformers

Several different methods that have been used for the investigating the seismic performance of electrical equipment, including transformers and bushings there are known. Two main standards groups are widely used: IEEE 693 in America and IEC in Europe.

IEEE Std 693-2005 “Recommended Practice for Seismic Design of Substations” [3] is a newly revised document covering the procedures for qualification of electrical substation equipment for different seismic performance level. The IEEE 693 strongly recommends that the equipment shall be qualified on the support structure that will be used at the final substation. In contrast, the IEC 61463 “Bushings-Seismic qualification” [4] is an IEC recommendation covering the seismic qualification of power bushings. It recommends executing of a dynamic analysis or vibration test. It is based mainly on static calculations introducing the coefficients to amplify the severity from the ground to the transformer. It must be noted, that bushings meeting the requirements of IEEE 693 will, in most cases, meet the requirements of IEC 61463.

Even if shake table tests are strongly recommended for seismic qualification of substation, the numerical analyses can be very helpful to determine seismic withstand of these products. Furthermore in some cases, where the tests are impossible because of weight and size (e.g. power transformers), this the only one way to determine the dynamic characteristic of the system.

1.3. Traditional Simulation Approaches

Seismic analysis of power systems is realized by estimation of the impact of a specific seismic loads an object or part thereof (equipment). Methods of Seismic analyses methods can be divided into the following types which are based on:

a) static approach,
b) quasi-dynamic approach,
c) dynamic approach.

Static analyses and quasi-static method are often used to simple equipment having the main frequency modes out of the dangerous seismic range (above 33 Hz). Such objects are qualified as ‘rigid’ ones. In the first method series of loads acting on the structure to represent the effect of earthquake ground motion are defined and applied to the component’s centre of gravity. The second method can be used for equipment having a few important modes in the seismic range. Forces shall be obtained by multiplying the values of the components mass by the coefficients which are used to amplify the ground accelerations: K – super-elevation factor, R – the response factor, and S – static coefficients.

For complex structures of power products with many modes within the seismic range the modal dynamic analysis is recommended by the standard, and this approach was used in the analyzed case. The standard specifies also explicit time history dynamic analysis (also based on modal dynamic approach), which should be performed if the results cannot be verified by measurements (for multiple, inter-connected heavy equipment). Alternatively response spectrum can be used for rough, conservative evaluation. Those two methods usually are based on the Finite Element Method (FEM).

1.4. Finite Element Method (FEM) for seismic analyses

The modal dynamic analysis of the bushing under seismic loads is presented below. In this method, the object under examination is represented by its geometrical CAD model. Once the geometric model has been created, a set of boundary conditions has to be specified (constraints and exciting forces) and applied to the geometrical model (Figure 1). Afterwards, a meshing procedure is used to define and break the model up into small volume elements (Figure 1).

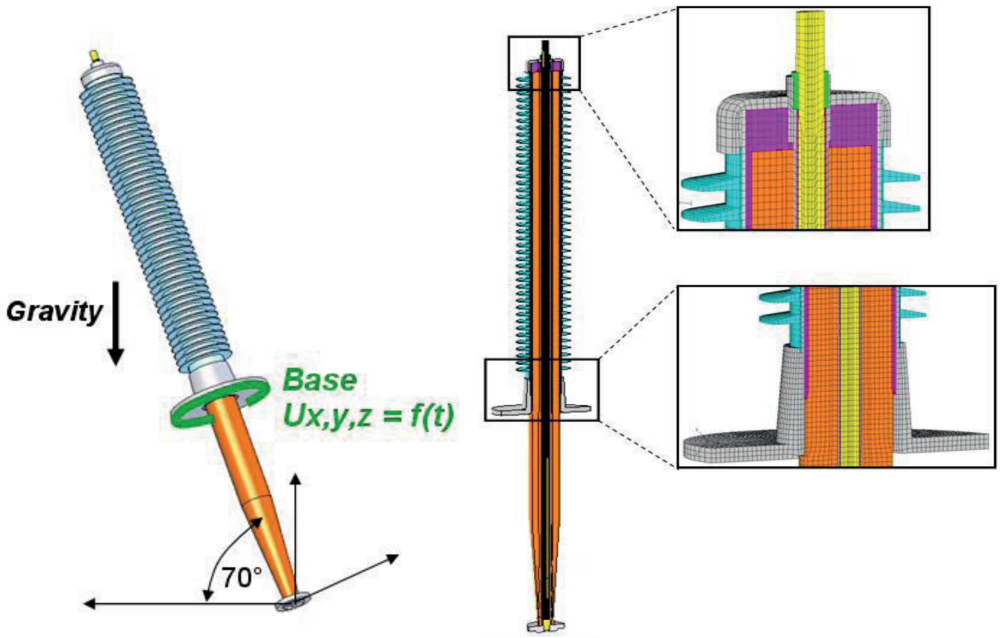

Figure 1 – Boundary conditions (left) and mesh of analyzed RIP bushing 230 kV (right)

In the final stage the results (accelerations, displacements, stresses and strains) are analyzed and compared with experiment (if possible).

In the presented approach, the structural evaluation for seismic events is based on linear analysis, using the structure's modes up to a limiting cut-off frequency, (33 Hz). Nonlinear effects such as contact or plasticity material model cannot be include in this approach.

The eingenvalue problem for natural frequencies (undamped finite model) is:

$$\left(-\omega^2 \mathbf{M} + \mathbf{K}\right)\Phi = 0 \tag{1}$$

where:

M - matrix (which is symmetric and positive definite)
K - stiffness matrix (which includes initial stiffness effects if the base state included the effects of nonlinear geometry and pre stress caused by gravity)
Φ - eigenvector (the mode of vibration)
ω - is the natural frequency

Once the modes are available, their orthogonality property allows the linear response of the structure to be constructed as the response of a number of single degree of freedom systems. In other words, the mechanical behavior of the bushing structure under base-motion is derived as linear superposition of its natural frequency modes.

Using this numerical approach for seismic analyses of HV transformer bushings, three different excitations referred to as sine sweep, earthquake time history and sine beat are usually performed. It was verified that the applied FEM methodology is able to predict the relative natural resonant frequencies, acceleration, and displacement for seismic qualification with good accuracy [5] presented in Table 1.

Table 1 - Natural resonance frequencies for simulated and tested transformer bushing

Natural resonance frequencies [Hz]			
Mode	Simulations	Measurements	**Difference [%]**
1	12.77	12.4	**3**
2	12.79	12.5	**3**
3	20.17	19.5	**4**
4	20.28	20.1	**1**
5	76.52	n.a.	n.a.

The application of advanced numerical simulations shows the potential to minimize further the experimental efforts on shake table qualification.

2. ADVANCED SEISMIC ANALYSES OF POWER TRANSFORMERS

2.1. Dynamic Behavior of the Bushing-Transformer System

In the literature we can find a lot of claims that the dynamic behavior of the bushing, mounted on transformer, is different than separate bushing that is seismically tested. The seismic response of the transformer-bushing system can be complex by interconnecting components. Furthermore, installed equipment can cause damage through connectors (bolts, rivets, weld). Thus, the seismic bushing tests with rigid frame will not take all critical situations into account. To quantify the effect of transformer on bushing dynamic characteristic and its seismic response, further investigation is needed [6]. The Finite Element Method (as for RIP bushing 230 kV) seems to be good for additional research in order to understand the dynamic response of transformer-bushing system. The study was prepared based on the modal analyses (similar as for RIP bushing 230 kV) in order to find natural frequencies of the analyzed model.

Three models: bushing, bushings together with turrets and top cover, transformer (without oil) were prepared and analyses were performed. The main results obtained are resonant frequencies presented in Table 2 and stress distribution shown in Figure 2.

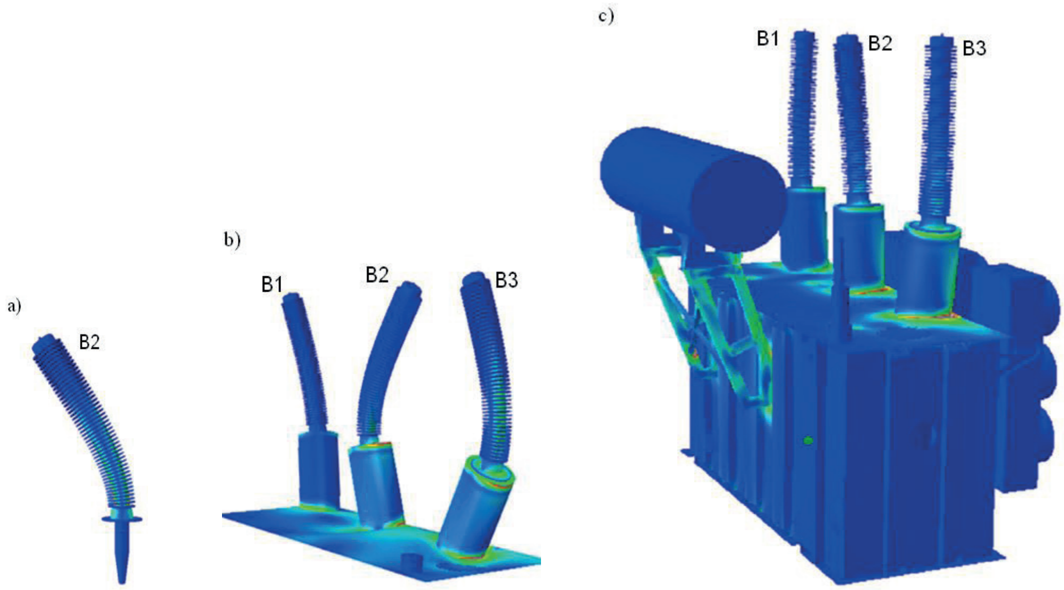

Figure 2 – Modes during modal analyses of a) bushing, b) bushings with top cover, c) transformer. B1 – bushing No. 1, B2 – bushing no. 2, B3 – bushing No. 3

Table 2 - Comparison of first natural frequencies [Hz] obtained from simulations for bushing, bushings with top cover, and the whole transformer

Bushing	Bushings with top cover			Bushing-Transformer system		
B2	B1	B2	B3	B1	B2	B3
14.13	5.54	18.38	20.34	6.4	7.08	6.1
14.13	22.99	26.46	25.83	8.36	7.38	7.08
	27.32	30.99	26.46	8.74	8.36	11.18
	33.28	33.28	32.04	10.44	8.74	17.47

Natural frequencies found were limited up to 33 Hz or 15 modes. For the last two cases frequencies are listed for both: the whole analyzed structure and separate bushings. The natural frequencies differ for three analyzed cases. For the last case (transformer) there are lower ones than for the first case (separate bushing). The performed simulations show that for comprehensive seismic analyses of transformer bushing whole system should be considered. Moreover, for power products that are liquid (oil) filled influence of the liquid on seismic loads should be verified.

2.2. Fluid-Structure Interaction (FSI) Co-Simulations

To find the right dynamic characteristic of the transformer-bushing system including tank, top plate, turrets and bushings numerous studies exist [1, 2]. Some activities are done in the area of seismic analyses of elevated tanks [7, 8, 9], ship industries and sea transport [10, 11] or storage tanks [12, 13] or its road transport of liquids [14]. But, generally, there is no clear statement about fluid influence on dynamic behavior of the transformer-bushing system.

Currently, usual approach in cases where strong interaction between fluid flow phenomena and stress effects exists is to perform structure and CFD analysis separately. Thus, the impact of flow induced forces on a structure and the impact of structure on the fluid flow are not considered. In an FSI co-simulation the analysis domains are coupled in that way, that the equations for each domain are solved separately. Loads and boundary conditions are exchanged between two domains at the common interface e.g. using MpCCI code [15]. Fluid-structure simulation capability allows fully coupled simulation approach and more precise modeling.

In the CFD the structure (tank) with fluid is modeled while in structural calculations only the structure is considered. CFD code is responsible for calculation of fluid flow. As a result, forces on the structure walls were delivered to the structural code and used as loads and boundary conditions. The new shape of the structure is given back to the CFD where the mesh update is prepared for next time increment. Finally we can get stresses, strains and deformation for the structure taking into account fluid dynamics. The scheme of the approach is presented in Figure 3.

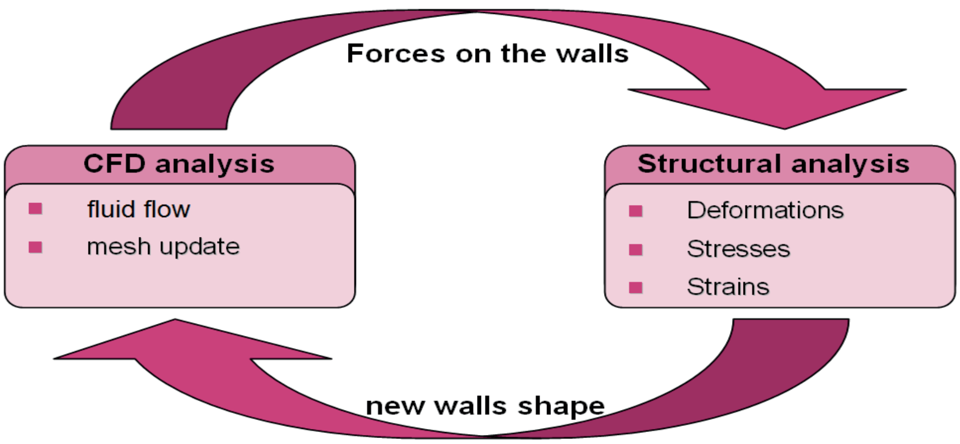

Figure 3 – FSI co-simulations seismic analysis approach

2.3. Acoustic Medium Approach for seismic analyses

Another approach to examine fluid influence during seismic loads is the way where a fluid is modeled as an acoustic medium. In case of as acoustic medium the equilibrium equation for small motions of a compressible, inviscid fluid flowing through a resisting matrix material can be represented by equation:

$$\frac{\partial p}{\partial x} = \gamma \dot{u} + \rho \ddot{u} = 0 \tag{2}$$

where:

p - is the dynamic pressure in the fluid (the pressure in excess of any initial static pressure),

x - is the spatial position of the fluid particle,

$\dot{u}$ - is the fluid particle velocity,

$\ddot{u}$ - is the fluid particle acceleration,

ρ - is the density of the fluid,

γ - is the "volumetric drag" (force per unit volume per velocity) caused by the fluid flowing through the matrix material.

Main assumptions of the constitutive behavior of the fluid are both inviscid and compressible. Thus, the bulk modulus of an acoustic medium relates the dynamic pressure in the medium to the volumetric strain by:

$$p = -K\varepsilon \tag{3}$$

where:

$\varepsilon = \varepsilon_x + \varepsilon_y + \varepsilon_z$ is the volumetric strain.

Both the bulk modulus K and the ρ density of an acoustic medium must be defined. The bulk modulus K can be defined as a function of temperature and field variables but does not vary in value during an implicit dynamic analysis using the subspace projection method or a direct-solution steady-state dynamic analysis [16]. For these procedures the value of the bulk modulus at the beginning of the step is used.

2.4. Coupled Euler-Lagrange Method

CEL (Coupled Euler - Lagrange) method implements possibility of interaction between Lagrange and Euler mesh formulation. In typical Lagrangian approach nodes of the finite elements are fixed within material. Consequently the finite element deforms as the material deforms. Precise values of displacement and distortion are defined by nodes coordinates. Lagrangian formulation is commonly used for solid mechanics problems. The difficulty arises in case of large deformations of analyzed objects. Excessive deformation of discrete mesh often occurs, what might lead to convergence problems and often inaccurate and useless results. In the opposite Eulerian approach introduces numerical grid and corresponding to it nodes as a discrete domain fixed in space. The material flows through the elements which not deforms as in Lagrange approach.

The CEL approach combines the advantages of Lagrange and Euler formulation and can be used in advanced seismic simulations. Sloshing of the fluid (oil domain) is solved using Eulerian formulation on a Cartesian grid that overlaps the Lagrange structure.

In considered case fluid like material was defined using linear U_s-U_p Equation Of State (EOS) model governed by the Mie-Gruneisen equation of motion. This relates to incompressible fluid model. In the EOS U_s –U_p Hugoniot form there are three input variables which must be defined before simulation. These are: c_0 – bulk speed of sound, s - is linear relationship between the linear shock velocity, U_s, and the particle velocity, U_p and Γ_0 - Gruneisen's gamma at the reference state.

Described approach was used to simulate transformer conserver tank partially filled with oil. Such setup would be difficult in representation using coupled acoustic-structural approach with expected large motions of the fluid (sloshing). Whole assembly was subjected to three axial time history ground motion which definition was based on "High level required response spectrum" defined in IEEE693 standard [3].

FE model was built using Eulerian solid and Lagrangian shell elements. All interfaces between structural parts were bonded - welded connection. At the bottom of the support structure ground motion accelerations were defined. Gravity load was applied globally.

Oil motion during time history test for first seconds of the ground motion is presented in Figure 4. One can see that CEL approach caught strong inertia of the fluid and its impact on the structure. This effect was not observed using coupled structural – acoustic approach. Concluding evaluation of fluid sloshing is one of the main benefits of presented method.

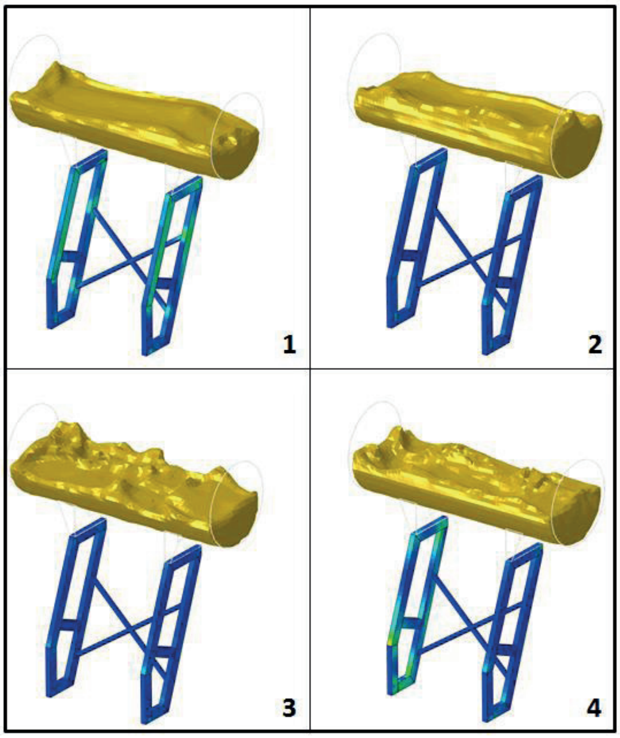

Figure 4 – Fluid motion during predefined ground motion

Important note is that CEL approach is usually solved using dynamic explicit integration scheme. This implicates several consequences. One of it is that stable time increment is strictly related to element size and density of material. More refined mesh requires very low time increment to keep on track solution stability. On the other hand Euler domain requires very fine mesh to represent fluid behavior and its interaction with Lagrange/structural component properly. Another issue is related to contact modeling and the interface between fluid and structural domain. During simulation it was observed that fluid has been separated from the structural domain. One can conclude that one of the possible reasons of such effect has been caused by imprecise definition of the viscosity of the fluid. Implemented methodology did not resolve near boundary layer effects. Presented approach was solved in time domain. Input based motion lasted ca. 30 s and covered all important dangerous frequency values.

3. CONCLUSION

Key components of substations are transformers and bushings. Past earthquakes show that their seismic performance has not been satisfactory. Understanding the seismic interactions between substations equipment like transformer-bushings-foundations and fluids is very important to proper assessments of seismic performance of substations and in qualifications of equipment.

In this paper the first results of study in ABB related to fluid influence on dynamic behavior of the system like transformer-bushing was presented. In order to simulate these complex phenomena three different approaches for seismic analyses were presented. One of them is built based on the FSI and combination of different software (CFD, structural, and coupling code) to cover Fluid dynamics and structural analyses. Other is based on acoustic modeling of fluid. The last one is based on the coupled Euler Lagrange formulations.

Consequently presented methods are introducing advantages and disadvantages. In case of full FSI approach where CFD and FEM method are coupled one can evaluate in details behavior of the fluid and its influence on the structural response. In case of complex geometries difficulty in mesh generation and remeshing process arises In this method iteration stability requires very low time increment what implies excessively long calculation time. Acoustic-structural approach is convenient and relatively fast method. Main benefit is that external coupling code is not required. By using acoustic elements user can evaluate maximum pressure which is generated by the fluid during vibration excitation. One must be aware that this method gives reasonable results when expected response of the structure has relatively low amplitude. In case of high structural amplification possible sloshing effect will not be captured. Acoustic-structural approach is often limited to time history calculations therefore it cannot be used in eg. response spectrum method. The last method (CEL) introduces coupling between Lagrange and Euler domain. Thus, it is possible to simulate large deformation and sloshing of the fluid. In this method integration scheme is based on explicit formulation what many times results in very small time increment and consequently long calculation time.

Taking into account above, all this approaches can be very helpful to determine the dynamic characteristic of the transformers and its equipment including fluid and can reduce time of design phase if there are used appropriate for analyzed cases.

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