

ROBERT PŁATEK, GRZEGORZ JUSZKIEWICZ*

COMPUTER AIDED SEISMIC ANALYSES FOR TRANSFORMERS

KOMPUTEROWE WSPOMAGANIE ANALIZ SEJSMICZNYCH TRANSFORMATORÓW

Abstract

In the paper a different numerical approaches for seismic analysis of the power products have been presented. Main focus was put on typical simulation methods defined by IEEE and IEC standards. In many cases substations such as transformers are filled with oil. Standards do not provide clear information about fluid influence on power equipment during seismic event. Due to that fact some investigations related with fluid filled substations were done and summarized in this paper. Three different simulation methods were investigated: Fluid Structure Interaction (FSI) approach using FEM, CFD and code coupling software, acoustic approach and CEL (Coupled Euler Lagrange) method using Lagrange and Euler element formulation.

Keywords: seismic analysis, Finite Element Method (FEM), Fluid Structure Interaction (FSI)

Streszczenie

W artykule przedstawiono różne podejścia numeryczne wykorzystywane do analiz sejsmicznych transformatorów. Głównie opisane metody symulacyjne, które są wskazane przez standardy IEEE oraz IEC. Jakkolwiek w tego typie produktach mamy często do czynienia z występującą tam cieczą, np. transformatory mocy a jego wpływ nie jest jasno określony przez powyższe standardy. W związku z powyższym trzy różne podejścia numeryczne do oszacowania wpływu cieczy na strukturę w produktach mocy zostały przedstawione. Są to: podejście oparte na metodzie Fluid Structure Interaction (FSI), podejście oparte na elementach akustycznych oraz podejście oparte na równaniach Lagrange oraz Eulera (Coupled Euler Lagrange).

Słowa kluczowe: analiza sejsmiczna, Metoda Elementów Skończonych, Fluid Structure Interaction (FSI)

* Mgr inż. Robert Płatek, mgr inż. Grzegorz Juskiewicz, ABB Corporate Research, Kraków.

1. Introduction

Substations 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 of substation. The standards indicate that the seismic qualifications for power equipment should be done by shake table testing. It is acknowledged that the supporting structure of the bushing (tank, top plate, turret 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 [2, 3]. 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.

The paper describes the traditional numerical approaches for seismic analysis of power products and study of the fluid influence on the dynamic characteristics of transformer-bushing and oil conservator system

2. Standards for power products

Historically there are known a several different methods that have been used for the justification of the seismic performance of electrical equipment, including transformers and bushings. 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" [4] 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" [5] 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.

For MV drives we have IEC 60721. According to the specification, device should withstand stationary and non-stationary vibration load defined by a frequency spectrum. Beside of seismic check specification defines also requirements considering transportation and operating conditions. In such cases very often response spectrum simulation technique is used.

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.

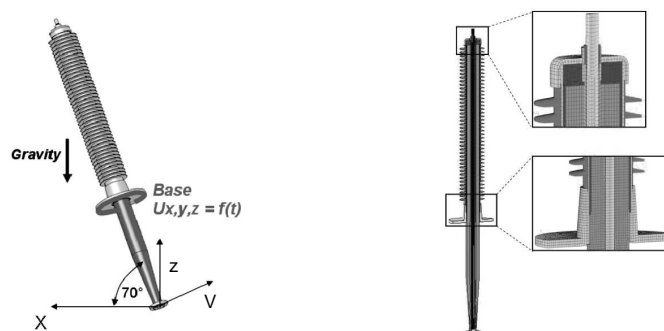
3. Traditional simulation approach

There are four seismic calculation procedures allowed:

- static,
- static coefficient,
- modal dynamic,
- time history dynamic.

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). 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, 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 equipments). Those two methods usually used the Finite Element Method (FEM). 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. Afterwards, a meshing procedure is used to define and break the model up into small volume elements (Fig. 1).



Rys. 1. Warunki brzegowe (z lewej) oraz siatka elementów skończonych analizowanego przepustu RIP 230 kV (z prawej)

Fig. 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). Non linear effects such as contact or plasticity material model cannot be include in this approach.

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

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

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

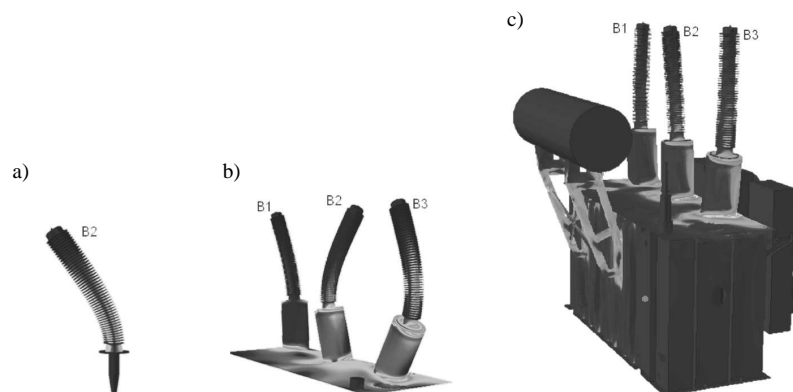
4. Dynamic behavior of the bushing-transformer system

Many specialists claim 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 equipments 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 [3]. 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 and stress distribution, Fig. 2. Comparison of resonant frequencies from each simulation is presented in Table 1. 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.



Rys. 2. Wybrane postacie drgań własnych dla: a) przepustu, b) przepustów wraz z płytą, c) transformatora

Fig. 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 1

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

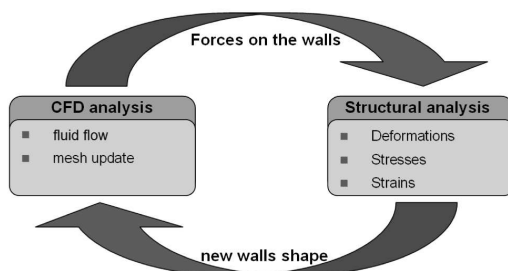
Bushing	Bushing with top cover			Transformer				
B2	All	B1	B2	B3	All	B1	B2	B3
14.13	3.29				2.92			
14.13	3.8				3.79			
	4.26				4.71			
	4.63				5.21			
	4.79				6.1			6.1
	5.54	5.54			6.4	6.4		
	18.38		18.38		7.08		7.08	7.08
	20.34			20.34	7.38		7.38	
	22.99	22.99			8.36	8.36	8.36	
	25.83			25.83	8.74	8.74	8.74	
	26.46		26.46	26.46	9			
	27.32	27.32			9.91			
	30.99		30.99		10.44	10.44		
	32.04			32.04	11.18			11.18
	33.28	33.28	33.28		17.47			17.47

5. Fluid Structure Interaction (FSI) co-simulations

There are numerous studies to find the right dynamic characteristic of the transformer-bushing system including tank, top plate, turrets and bushings [2, 3]. But in all these studies the fluid is neglected. Some activities are done in the area of seismic analyses of elevated tanks [7], ship industries, and sea transport [8, 9]. 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. 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, Fig. 3. Finally we can get stresses, strains and deformation for the structure taking into account fluid dynamics.



Rys. 3. Podejście bazujące na metodzie FSI
Fig. 3. FSI co-simulations seismic analysis approach

6. Acoustic medium approach

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:

$$\frac{\partial p}{\partial x} = \gamma \dot{u} + \rho \ddot{u} = 0, \quad (2)$$

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:

$$p = -K\varepsilon, \quad (3)$$

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 [11]. For these procedures the value of the bulk modulus at the beginning of the step is used.

7. Coupled Euler-Lagrange method

CEL (Coupled Euler-Lagrange) method allows interaction between Lagrange and Euler mesh formulation. In typical Lagrangian approach nodes of the finite elements are fixed within material. The finite element deforms as the material deforms. Exact values of displacement and distortion are defined by elements. Therefore, the number of elements is highly affecting calculation time and results. Lagrangian formulation is very useful for solid mechanics problems. In case of large deformations of analyzed objects excessive deformation of finite elements often occur. This may cause convergence problems and often inaccurate and useless results. In Eulerian approach numerical grid and corresponding to it nodes are fixed in space. The material flows through the elements which not deform. The Eulerian mesh is typically a simple rectangular grid of elements constructed to extend well beyond the Eulerian material boundaries. This gives the “space” in which material can freely move and deform.

The CEL approach combines the advantages of Lagrange and Euler formulation. The fluid is solved using Eulerian formulation on a Cartesian grid that overlaps the Lagrange structure. Such approach is very useful in analysis of power products where sloshing effect of the oil shall be considered.

Material model for Eulerian instance was defined using *EOS* (Equation of State) method and Newtonian viscous shear model. A linear *Us-Up* model was chosen. It requires severe input parameters. First one is described in equation (5).

$$c_o = \sqrt{\frac{K}{\rho}}, \quad (5)$$

where:

- C_o – bulk speed of sound,
- K – bulk modulus of the fluid,
- ρ – density of the fluid.

Beside of bulk speed of the sound *Us-Up* model requires also definition of relation between linear shock velocity and velocity of the fluid particle. Described relation is presented in equation (6):

$$s = \frac{dU_s}{dU_p}, \quad (6)$$

where:

U_s – linear velocity,
 U_p – particle velocity.

One must be aware that speed of the sound parameter is not equal to particle speed. While sound wave moves relatively fast particle oscillates around its original with much smaller velocity in comparison to wave speed. Additionally Grüneisen parameter (Γ_o) was used in the material model.

CEL approach was used to simulate transformer conservator tank filled with oil. The analysis was performed in dynamic manner. 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 [4].

Finite element model was built using Eulerian solid and Lagrangian shell elements. All interfaces between structural parts were bonded. This gave approximation of 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 Fig. 4. One can see that CEL approach caught sloshing effect of the fluid and its dynamic interaction with the shell structure.



Rys. 4. Ruch cieczy podczas wymuszenia

Fig. 4. Fluid motion during predefined ground motion

The Coupled Euler Lagrange approach gives opportunity of simulation highly dynamic for oil filled power products. CEL approach is available for explicit integration scheme. Simulation of long term dynamic events (5 s) makes computation time much longer in comparison to linear dynamic method.

8. Conclusions

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 equipments like transformer-bushings-foundations and

fluids is very important to proper assessments of seismic performance of substations and in qualifications of equipments.

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.

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