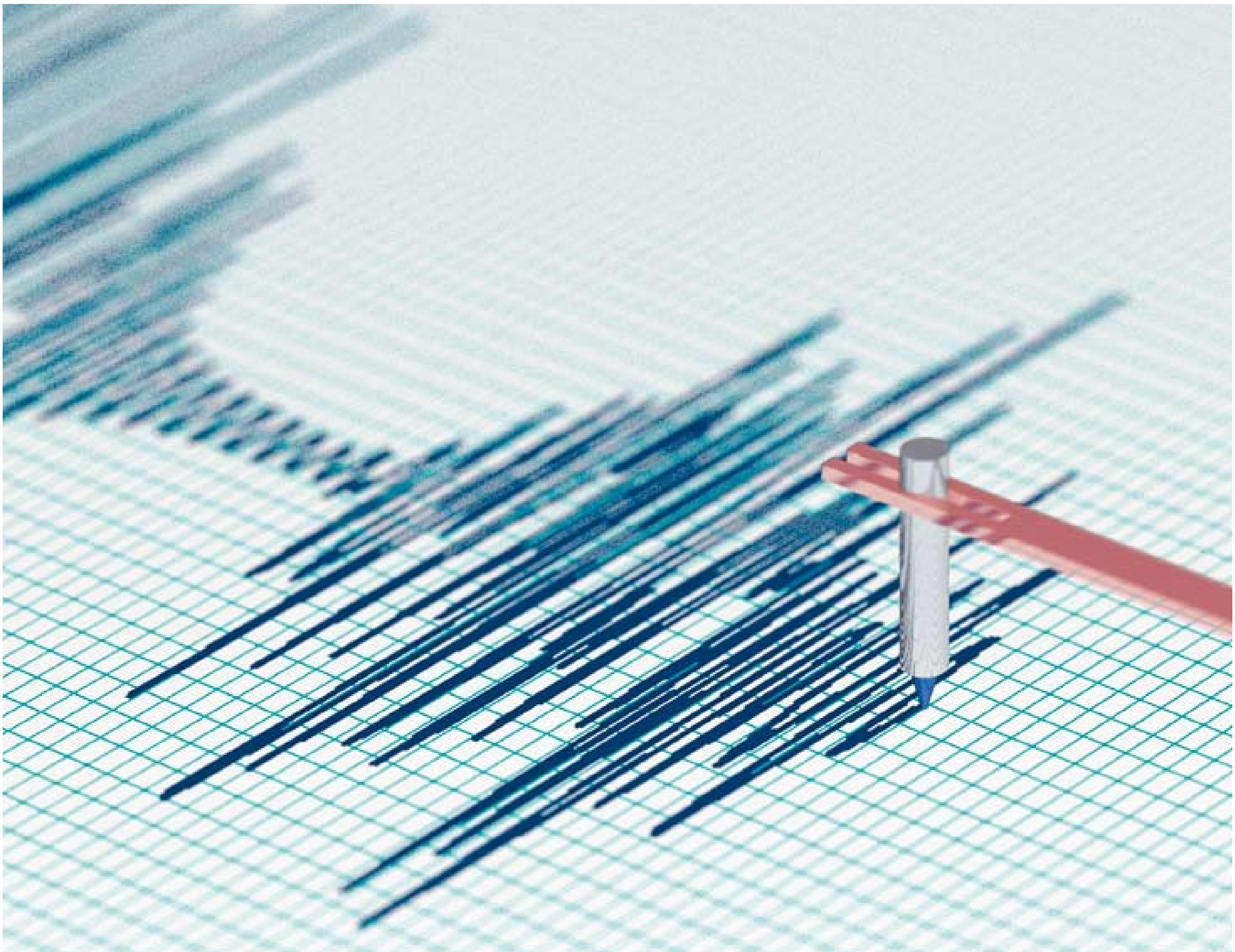
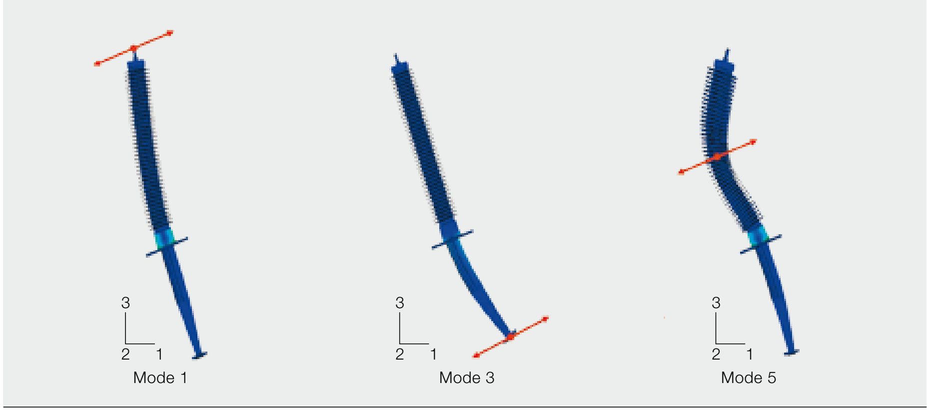


Seismic performance

Advanced seismic analyses of power products

ROBERT PLATEK, BOGUSZ LEWANDOWSKI – Earthquakes have the potential to wreak great havoc, including loss of human life, and cause extensive damage to infrastructure. Besides the actual damage caused to utility installations, the time taken to reestablish normal operation translates into further costs in terms of lost opportunities and productivity. Just as construction technology is continuously making progress and buildings are becoming more and more earthquake-proof, electrical equipment is also being designed to survive such events unscathed. Making power products earthquake-proof is no easy task. A large transformer including its foundations, tank, bushings, top-plate and connections is too large to fit on a shake-table, and the individual testing of these components is not necessarily representative of their performance when assembled as a system. Furthermore looking at these components together is still insufficient as the liquid inside the system will further modify overall seismic performance. ABB has developed a sophisticated combination of testing and different simulation methods leading to a better understanding of the seismic performance of the combination, permitting the development of transformers ready to survive the next earthquake.

1 Selected mode shapes for 230kV SeismicRIP™ transformer bushing (deformations are magnified by a scale factor).



Several different methods exist for investigating the seismic performance of electrical equipment. These methods usually involve static calculations to estimate the forces generated during a seismic event of a given ground acceleration, and then compare these to the capability of the equipment. The latter data may be derived from calculations or from actual measurements.

The two main international groups of standards used for this work are IEEE 693 and IEC 61463. IEEE 693-2005, "Recommended Practice for Seismic Design of Substations" [1] is a newly revised document covering the procedures for qualification of electrical substation equipment for different seismic performance levels. IEEE 693 strongly recommends that equipment should be qualified on the support structure that will be used at the final substation.

In contrast, IEC 61463 "Bushings – Seismic qualification" [2] is an IEC recommendation covering the seismic qualification of transformer bushings. Bushings meeting the requirements of IEEE 693 will, in most cases, also meet the requirements of IEC 61463.

Even though shake-table tests are strongly recommended for seismic qualification of critical components, numerical analyses can be very helpful in determining seismic withstand of these products. Furthermore, in some cases where tests are impossible due to the great weight of the equipment (eg, power transformers), the latter is the only one way to determine the dynamic characteristic of the system.

SeismicRIP bushing analysis

Complex structures may have many different resonant modes [1] within the dangerous seismic range. ABB thus performs modal dynamic analyses on them. The numerical analyses of the 230 kV SeismicRIP™ transformer bushing under seismic loads were performed using the finite elements method (FEM). In the approach presented here, 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).

New simulation tools should be always verified experimentally. Accuracy can then be evaluated and advantages and limitations recognized.

Once the resonance modes are identified, their orthogonality property [2] 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 ground-motion is derived as a linear superposition of its natural frequency modes. Depending on the excitation spectrum, individual natural frequencies can have different influences on the resultant movement → 1.

Simulations show very good agreement with test measurements. Natural resonant frequencies were found to differ by a maximum of one to four percent. For maximum accelerations at the measurement point (top of the bushing) the deviation was between 3 and 14 percent [3]. The results of this verification are valuable in the further development of numerical tools for seismic calculations.

Dynamic behavior of the bushing-transformer system

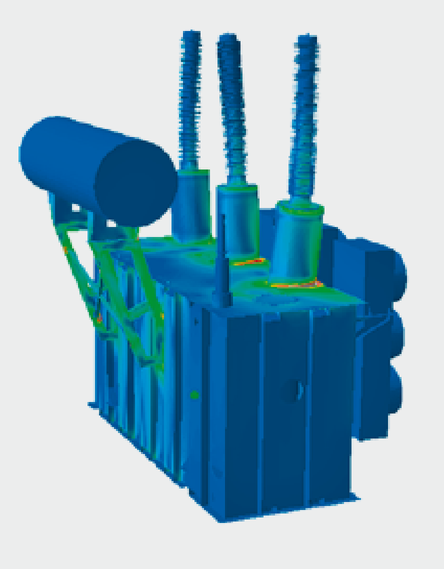
Many experts claim that the dynamic behavior of a bushing is different mounted on a transformer than it is when tested separately. Indeed, the seismic response of the transformer-bushing combination

Footnotes

1 A mode is the pattern of motion in which a body vibrates. Normally a body can vibrate in several basic modes as well as various possible superpositions thereof. For example a beam with fixed ends can vibrate in the shape of a half-period sine-wave, but can also be made to vibrate in the shape of higher-frequency sine waves. A complex three-dimensional solid can display many more modes than this simple one-dimensional example.

2 Orthogonal vibration modes are modes that do not lead to mutual excitation.

2 Distribution of stresses in a power transformer under seismic load



3 The first natural frequency of the bushing is affected by its mounting.

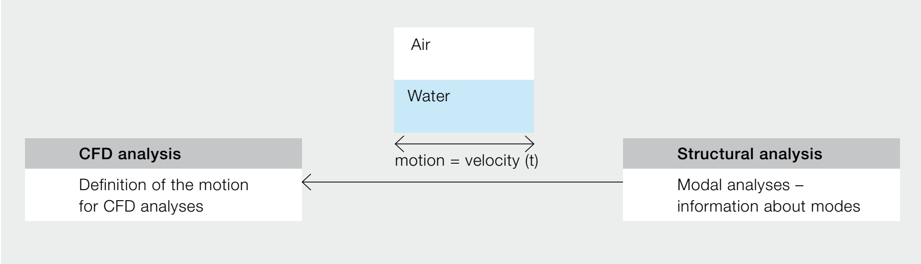
	Frequency (Hz)	
LP	Bushing	Bushing with top plate, turrets, and tank
1	14.13	7.08
2	14.13	7.38
3	–	8.36
4	–	8.74

The first natural frequencies of the bushing are different when mounted on the rigid frame than they are when mounted on the power transformer.

can be influenced by interconnecting components. Furthermore, equipment installed in the field can cause damage through its connectors [4]. Further investigation is required to quantify this effect. The FEM (for the RIP-type 230 kV bushing) appears to be a good area for additional research in order to understand the dynamic characteristic of the transformer-bushing system.

The simulations performed for both cases (separate transformer bushing, and power transformer with bushings → 2) show that the dynamic behavior is different for each case. The natural resonant frequencies of separate simulated transformer bushings are different from simulated bushings mounted on the transformer → 3.

4 First step of an FSI-based seismic analysis



The results clearly confirm that comprehensive seismic analyses of transformer bushings require the entire system to be considered.

Fluid structure interaction (FSI)

There have been numerous studies looking into the correct dynamic characteristic of the transformer-bushing system (including the tank, top plate, turrets and bushings [4, 5]). None of these studies, however, consider a very important influence: the coolant fluid. Studies do exist that look at the influence of fluid on the seismic response of elevated tanks [6], and also at such structures in marine applications and sea transportation [7]. But, none of these lessons was clearly applicable to the dynamic behavior of a transformer-bushing system.

To examine the fluid's influence on dynamic characteristics, an investigation using fluid structure interaction (FSI) was proposed. The FSI approach is based on data exchange between the simulation tools that model fluid flow and mechanical behavior.

FSI-based seismic analyses

The whole seismic analysis (sine sweep, earthquake time history and sine beat test) is a complex procedure. Thus, the sine sweep test, in which the modes and their shapes are identified, must be prepared in such way that the fluid is modeled as an acoustic medium. Based on this step it is possible to define initial conditions (motion) for CFD (computational fluid dynamics) analyses → 4.

The full FSI method is then applied in the next step → 5. In the CFD part, the structure (tank) is modeled with fluid, while in the structural calculations it is considered in isolation. CFD code is also used to simulate the effects of air flow on the fluid. The forces on the structure's walls are thus supplied to the structural tool and used as boundary conditions. The new shape of the structure is in turn given back to the CFD where the mesh update is prepared for next time increment. Stresses, strains and deformation of the structure are obtained taking into account fluid dynamics.

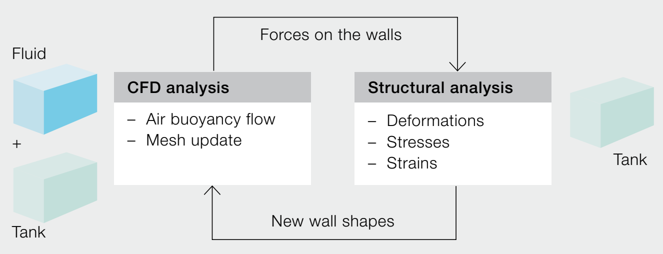
Experimental verification of proposed methodology

New simulation tools should be always verified experimentally. Accuracy can then be evaluated and advantages and limitations recognized. One of the objects used for this experimental verification was a prototype JUK 145 high-voltage combined instrument transformer. The measurement stand is shown in → 6a.

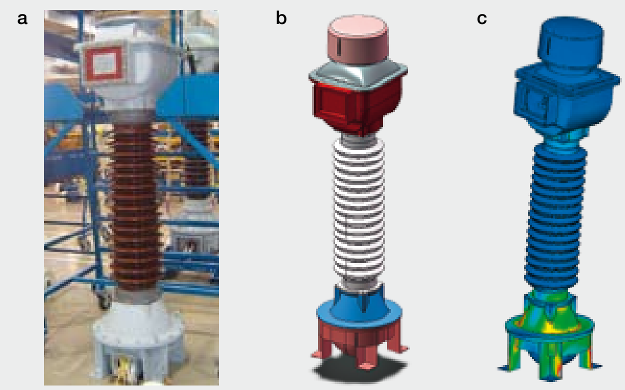
Simulations show very good agreement with test measurements. Natural resonant frequencies were found to differ by a maximum of one to four percent in case of SeismicRIP bushing analysis.

Using the simulation approach based on FSI (acoustic medium), a 3D model was prepared → 6b and the modal analyses of the transformer were performed on this → 6c. The comparison of results (measurements vs. simulations) is presented in → 7.

5 Second step of an FSI-based seismic analysis



6 Expermintal verification of simulation



6a Analyzed HV IT product
6b 3D model of HV IT
6c Stress distribution during the first calculated mode

7 Comparison of natural frequencies, measurements versus simulations using FSI based approach

LP	Measured frequency (Hz)		Calculated frequency (Hz)	
	Dry	Oil-filled	Dry	Oil-filled
1	8.5	5.4	6.21	5.09
2	10.5	6.2	13.88	11.17
3	24.6	24	25.39	16.52
4	25.4		27.5	19.56
5			28.64	20.64
6			28.85	23.75

The next step was to prepare seismic tests in the laboratory. The JUK 145 successfully passed seismic qualification based on IEC 60068. Full FSI-based seismic simulations are planned and these will permit the tool to be further verified.

A step forward in seismic simulations

Shake table testing of bushings has demonstrated good performance of these components in terms of the general response based on the IEEE 693 [8].

The coolant fluid was found to have a significant effect on the seismic performance of the transformer and bushing assembly

Applied FEM methodology for SeismicRIP bushings displays the potential to be able to predict relative acceleration and displacement with good accuracy for seismic qualifications [3]. However, to go beyond this, understanding of seismic interactions between substations equipment and fluids is vital. Development of this can improve seismic performance of substations and liquid-filled products.

The further study of fluid influence on the seismic qualifications of liquid-filled products is continuing. Undoubtedly, the proposed approach is unique and helps to understand the dynamic behavior of entire systems, permitting their seismic performance to be improved.

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Further reading

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