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 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.

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 (e.g. power transformers), the latter is the only one way to determine the dynamic characteristic of the system.

Seismic RIP bushing analysis

Complex structures may have many different resonant modes within the dangerous seismic range. ABB thus performs modal dynamic analyses on them. The numerical analyses of the 230 kV Seismic RIP 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).

Once the resonance modes are identified, 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 underground 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. (Fig. 1)

Simulations show very good agreement with test measurements. Natural resonant frequencies are listed in Table 1.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
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<tbody>
<tr>
<td>14.13</td>
</tr>
<tr>
<td>14.13</td>
</tr>
<tr>
<td>8.36</td>
</tr>
<tr>
<td>8.74</td>
</tr>
</tbody>
</table>

Table 1: The first natural frequency of the bushing is affected by its mounting.
frequencies were found to differ by a maximum of 1 to 4%. For maximum accelerations at the measurement point (top of the bushing) the deviation was between 3 and 14% [3]. The results of this verification are valuable in the further development of numerical tools for seismic calculations.

Dynamic behaviour of the bushing-transformer system

Many experts claim that the dynamic behaviour of a bushing is different mounted on a transformer than it is when tested separately. Indeed, the seismic response of the transformer-bushing combination 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 (Fig. 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 (Table 1).

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 such structures in marine applications [6]. A study with the tank, top plate, turrets and bushings was clearly applicable to these lessons was clearly applicable to the influence of fluid on the seismic response of elevated tank [6], and also at 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 behaviour.

**Table 2: Comparison of natural frequencies, measurements versus simulations using FSI based approach**

<table>
<thead>
<tr>
<th>LP</th>
<th>Measured frequency (Hz)</th>
<th>Calculated frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry O-filled</td>
<td>Dry O-filled</td>
</tr>
<tr>
<td>1</td>
<td>8.5</td>
<td>6.21</td>
</tr>
<tr>
<td>2</td>
<td>10.5</td>
<td>13.88</td>
</tr>
<tr>
<td>3</td>
<td>24.6</td>
<td>25.39</td>
</tr>
<tr>
<td>4</td>
<td>25.4</td>
<td>27.5</td>
</tr>
<tr>
<td>5</td>
<td>28.64</td>
<td>20.64</td>
</tr>
<tr>
<td>6</td>
<td>28.85</td>
<td>23.75</td>
</tr>
</tbody>
</table>

The full FSI method is then applied in the next step (Fig. 4). 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 recognised. 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 Fig. 5a.

Using the simulation approach based on FSI (acoustic medium), a 3D model was prepared (Fig. 5b) and the modal analyses of the transformer were performed on this (Fig. 5c). The comparison of results (measurements vs. simulations) is presented in Table 2.

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].

**References**


Contact Shivani Chetram, ABB SA,
Tel 010 202-5000,
shivani.chetram@za.abb.com