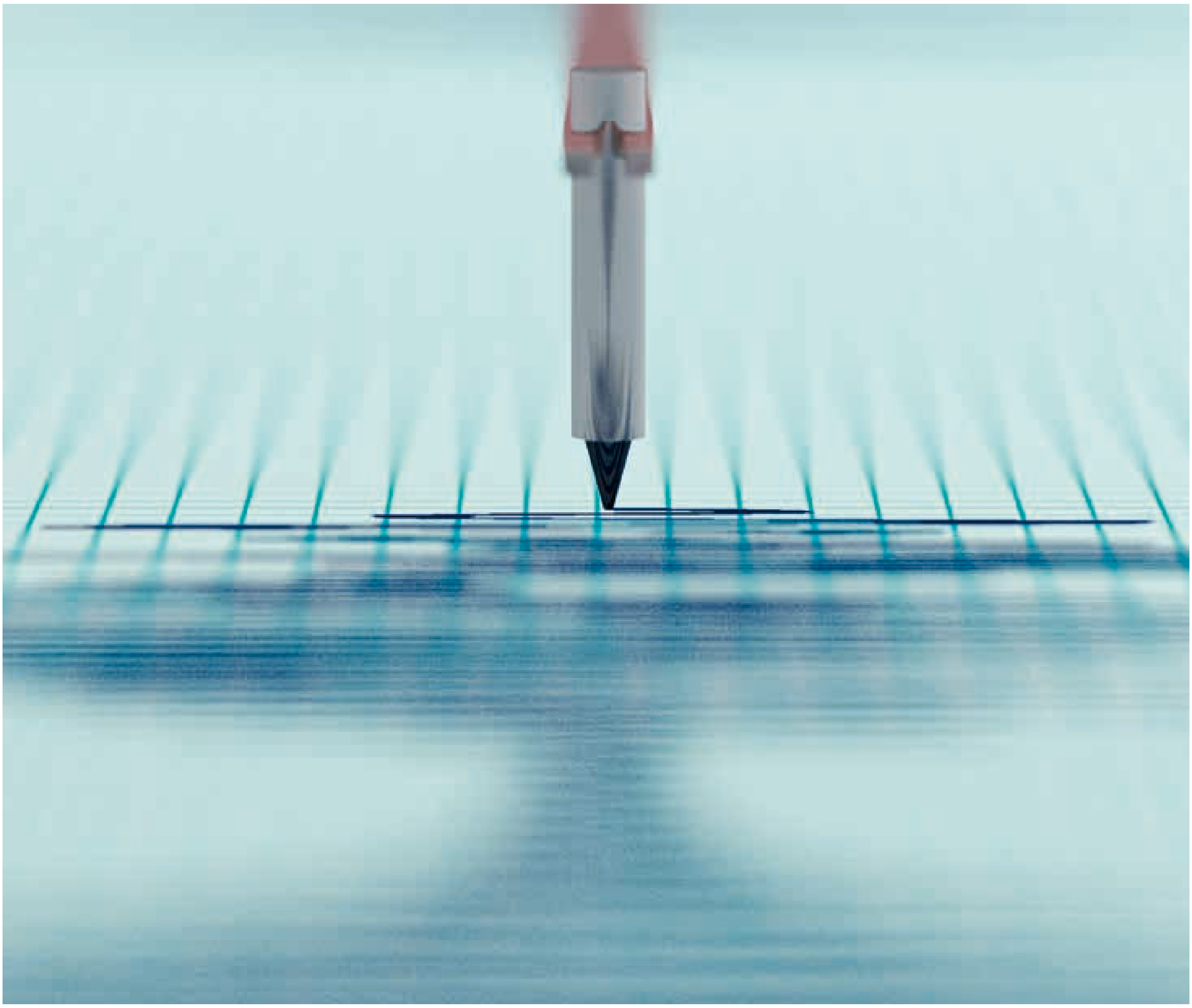


# Shake, rattle and roll

## Helping equipment to withstand earthquakes and reduce noise with design simulations

ROBERT PŁATEK, GRZEGORZ JUSZKIEWICZ, MICHAŁ KOZUPA, GRZEGORZ KMITA, PER LINDHOLM, ROMAIN HAETTEL, MUSTAFA KAVASOGLU, ANDERS DANERYD, JOHAN EKH – Nowadays, to thoroughly evaluate complex power systems, one must perform a variety of tests to tweak and optimize a design for best performance. Before delivery, products and systems must be cross-checked under a variety of operating and environmental conditions to determine their limits. One important aspect during the design of power products is noise and vibration. Since ABB's power products must exhibit low noise and high seismic resilience, it is crucial to prove that the design is efficient and reliable and will also satisfy customer specifications and environmental regulations.

Reliability and security of power systems, especially in areas prone to earthquakes, depends on the seismic robustness of its components.

Seismic loads are some of the dynamic loads that may affect not only the buildings, but also power devices. The Richter scale, as a measure of earthquake strength, tells little about the ground motion, which depends on the frequencies of the surface waves and on the properties of the subsoil, etc. Reliability and security of power systems, especially in areas prone to earthquakes, depends on the seismic robustness of its components. Devastating earthquakes can have a direct impact on the electric power industry and consequently all relevant power products, operating in seismically active areas, should be designed and tested to guarantee high seismic performance.

Where shake table tests are impossible due to the great weight of the equipment, numerical analysis is the only way to determine the dynamic characteristic of the system.

Making power products earthquake-proof is no easy task. However, ABB's many years of experience in this field help to understand the nature of seismic events. Efficient analyses of seismic loads, based on industrial standards, go far toward developing innovative approaches for these types of problems.

## Seismic standards and tests

The two main international groups of standards used for investigating seismic performance are IEEE 693 [1] and IEC 61463 [2]. IEEE 693-2005, "Recommended Practice for Seismic Design of Substations," 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. Shake-table testing of bushings has demonstrated good performance of these components in terms of the general response based on the standard IEEE 693 → 1. 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, for example power transformers, numerical analysis is the only way to determine the dynamic characteristic of the system.

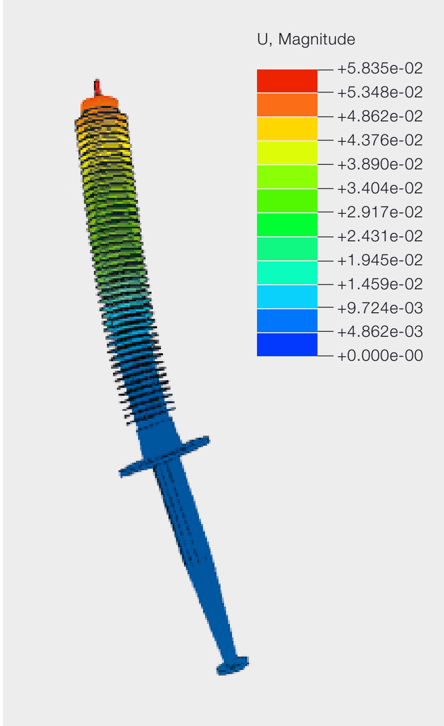
## Modeling methods for seismic analyses

Different analyses are used for the seismic verification 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 comparing these to the capability of the equipment. For rigid structures, with the lowest natural frequencies higher than 30 Hz, there is no amplification factor of the ground motion and the highest load is equal to the ground acceleration; therefore a static evaluation

**Title picture**
The earthquake robustness and environmental noise of power products are being improved by numerical analysis.

1 Physical and simulated tested of a RIP 230 kV bushing

1a RIP 230 kV bushing under seismic test




1b The bushing's calculated first mode of natural frequency

can be used. However larger structures commonly have natural frequencies lower than 30Hz. The most common method used to calculate seismic loading is response spectrum analysis, in which the response of the different eigenmodes in the structural designs are summated. It is based on a modal analysis of the natural frequencies and eigenmodes of the structure. Another popular method is "sine-beat" simulation where the structure is enforced by a certain number of sine waves of a frequency equal to the first natural frequencies below 33 Hz. The next step in this time-domain method is "time history," where the structure is subjected to random acceleration loads of at least 20 seconds, which corresponds to spectrum definition. At the end, deformations, strains and stresses are analyzed and seismic withstand can be evaluated. The applied methodology for seismic RIP-type (resin impregnated paper) bushings shows the potential to predict relative acceleration and displacement with good accuracy for seismic qualifications [3]. However, to go beyond this, an understanding of seismic interactions between substation equipment and fluids is vital.

## Challenges of seismic modeling

Many specialists claim that the seismic response of the transformer-bushing system can be complicated by interconnecting components [4, 5]. Furthermore, installed equipment can cause damage as a result of installation connections (bolts, rivets, weld). Thus, seismic bushing tests with a rigid frame will not take all critical situations into account and further investigation is needed. Performed simulations of a transformer's tank and its components show that for comprehensive seismic analyses, the whole transformer-bushing system should be considered → 2. Moreover, for power products that are liquid (oil) filled the influence of the liquid on seismic loads should be verified. Better computing power means the complexity of structural models can be increased to include a combination of more detailed geometry description or multiphysics. To examine the fluid's influence on dynamic characteristics, an investigation using fluid structure interaction (FSI) was used. The FSI approach is based on data exchange between the simulation tools that model fluid flow and mechanical behavior. In computational fluid dynamics (CFD) the fluid filled tank is modeled while in structural calculations only the structure is considered. CFD code is responsible for the calculation of fluid flow. As a result, forces on the structure walls are 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 the next time increment. The outcome is that it is possible to see the stresses, strains and deformation for the structure, taking into account fluid dynamics.

> Today, the limitation of noise pollution is a matter of increasing importance worldwide.

## Vibro-acoustics

Today, the limitation of noise pollution is a matter of increasing importance worldwide. Therefore, when designing power products, low sound and vibration levels are mandatory to comply with customer specifications or environmental regulations. It is thus essential to predict sound levels with a sufficient accuracy at an early stage of the product design to select the most appropriate strategy for noise control.

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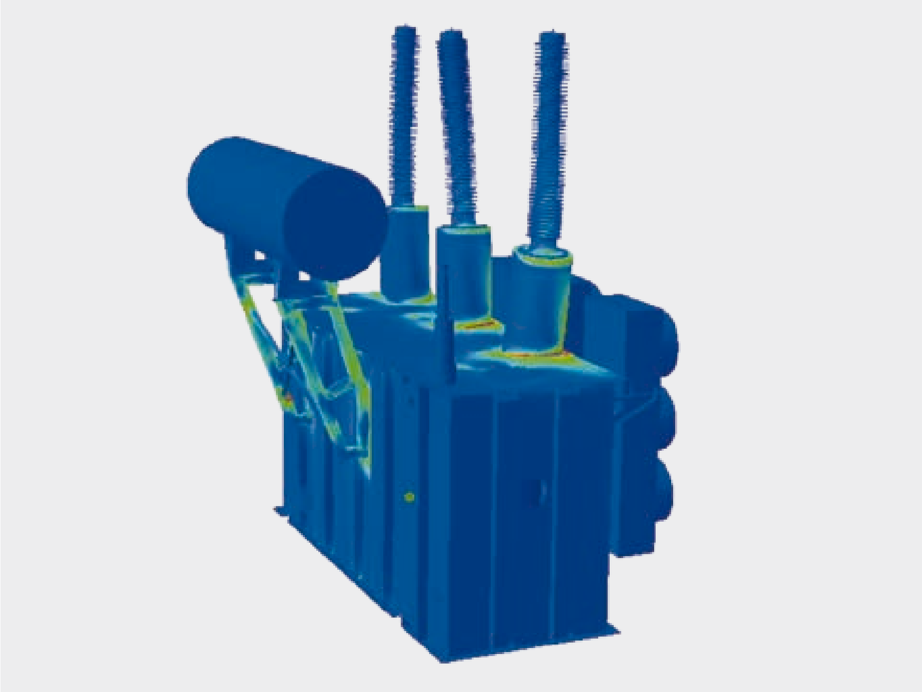
2 Stress distribution of the whole power transformer during seismic analysis



## Noise generation

The specific mechanism implying sound and vibration generation for many ABB products is explained by the energy conversion chain ➔ 3. The energy conversion procedure constitutes a typical multiphysics phenomenon involving electromagnetism, mechanics and acoustics. The interaction between alternating current and the associated magnetic fields, results in varying forces generating structural vibrations which are eventually radiated as sound. The described multiphysics mechanism can be observed in many ABB products, such as transformers or capacitors. Due to the relative complexity of those products, advanced prediction tools are generally required to accurately describe the interactions of the various design parameters and the coupling between the physical fields. Numerical analyses are the key tool, helping to understand noise generation issues and developing efficient noise abatement solutions.

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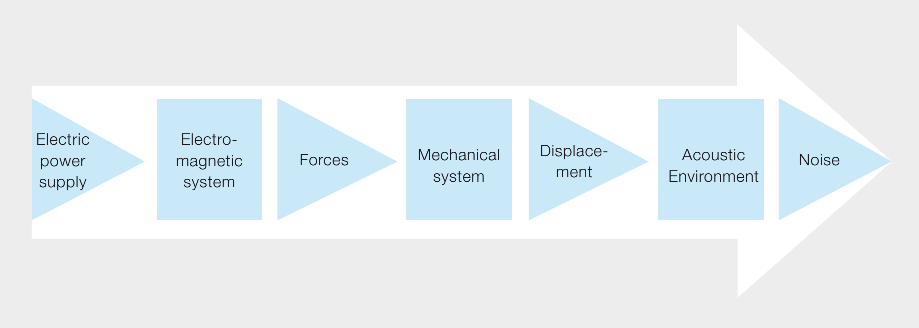
## Vibro-acoustic simulation examples

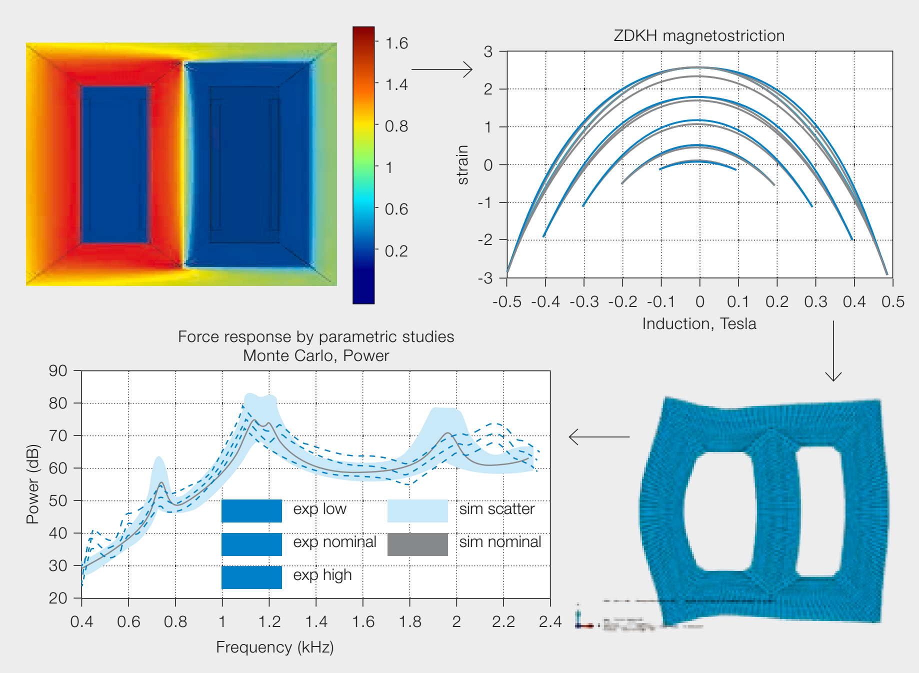
At ABB's research centers, finite-element and boundary-element methods are used to simulate the vibro-acoustic performance of various ABB products. The typical example of multiphysics and multiscale simulations is the noise generation in oil-immersed power transformers where two particular sources of noise generation can be distinguished: core noise (commonly named "no-load noise"), and winding noise (commonly named "load noise").

After applying current to the transformer windings, a magnetic flux is generated in the transformer core. So-called grain-oriented electrical steel, which is the main material for transformer cores, has a nonlinear anisotropic characteristic property called magnetostriction, essentially meaning a core dimensional change due to the point-wise alternating or rotational magnetic flux [6]. These frequency-dependent magnetostriction forces cause core vibrations resulting in no-load noise. The magnetic flux density in the core, magnetostriction strain due to different levels of flux density, typical deformation shape for the transformer core

3 Energy conversion chain: from electric supply to sound




4 Core noise prediction and validation of laboratory scale core




structure and finally sound power levels, which present a good agreement with measured levels, are shown in → 4.

Load noise appears due to the interaction between the stray field and the current flowing in the winding, which produce Lorentz forces inducing winding vibrations [7, 8].

A well-defined vibration model brings information about large amplitude areas with potential for damping.

The vibration of core and winding are transmitted through the insulating oil, core supports and clamping structures, to the tank walls where they are eventually radiated to the surrounding air as noise. This tank vibration can be related to the emitted sound power by computing the surface's acoustic intensity.

→ 4 presents a typical approach for a transformer-like product. The procedure starts with the electromagnetic calculations, which give mechanical forces applied to the structure. Crucial for appropriate vibration image on the tank is the structure-fluid-structure path, including interface and phenomena occurring in the oil itself. A well-defined vibration model of the outermost surfaces not only gives a proper acoustic radiation pattern but also brings information about large amplitude areas with potential for damping.

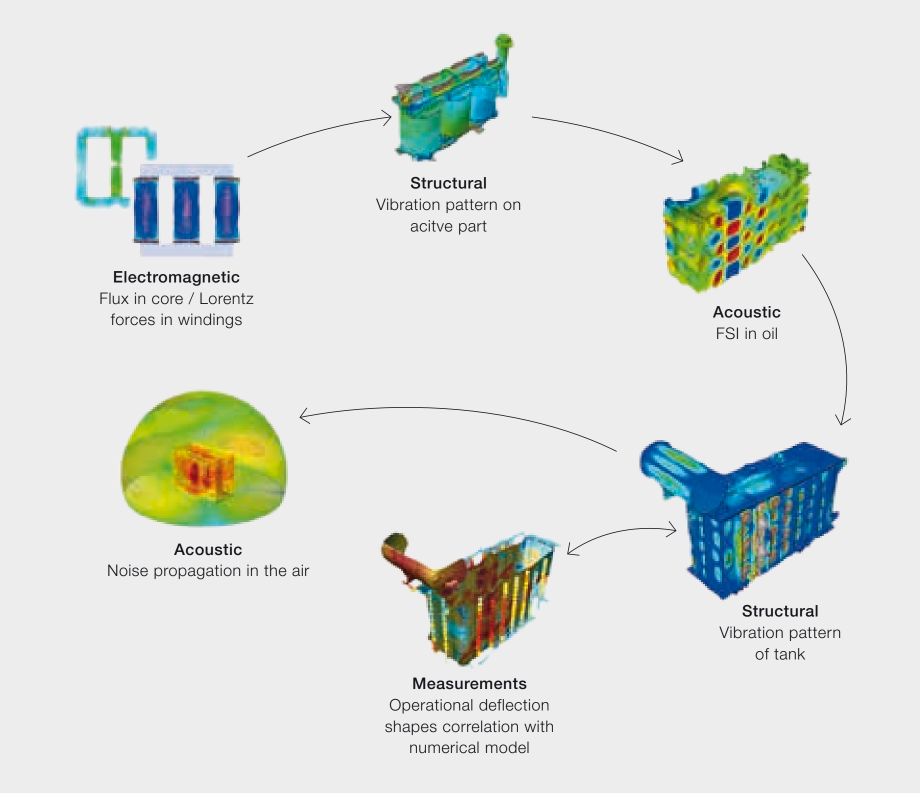
This simple model will predict the noise produced by capacitors on site with an accuracy of ±1.5 dB, long before any component is built.

High-voltage power capacitors used in SVC (static var compensator) and HVDC (high-voltage direct current) plants constitute a major source of noise. Therefore, a prediction tool has been developed to estimate the sound generated by capacitors. The transfer function between input voltage and sound power can be calculated analytically by describing the capacitor as a longitudinally oscillating beam subjected to alternating Coulomb's forces. This simple model, in combination with the estimated service current spectra for the planned power plant, will predict the noise produced by capacitors on site with an accuracy of ±1.5 dB, long before any component is built.

## Vibro-acoustic experimental validation

A full analysis of any structural system, in which the acoustic response is the output, must start with accurate operational modal analysis and good correlation with the system eigenvalues derived from the real test data. Measurements carried out in a controlled environment on well-designed scale models, subjected to a realistic excitation, are necessary for a first detailed validation. When the laboratory testing has been completed and is well understood, complementary measurements must be carefully planned and performed on full-scale products to finalize the validation procedure. Advanced measurement techniques, such as laser

5 Multiphysics prediction tool development




Doppler vibrometry (LDV) can be helpful in this procedure. The LDV technique is able to provide the 3-D vibration patterns of the transformer during load or no-load conditions creating so-called operational deflection shapes (ODSs) ➔ 5 [9]. The ODS patterns can be directly compared to the numerical analysis and if necessary some improvements of the model can be introduced.

## After the shocks

Modern prediction tools such as multiphysics software combined with computing power enable detailed and efficient studies showing the complex interactions of the design parameters and the effects of the material properties on the sound power levels. Appropriately correlated numerical models constitute the foundation for "virtual prototyping," meaning that products and systems can be virtually tested and enhanced without the need to produce "tangible" prototypes. Such numerical simulations are an often unseen, but essential, part of reducing noise pollution and ensuring continuity of power supply, allowing consumers to work and sleep peacefully: even if the earth does move.

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