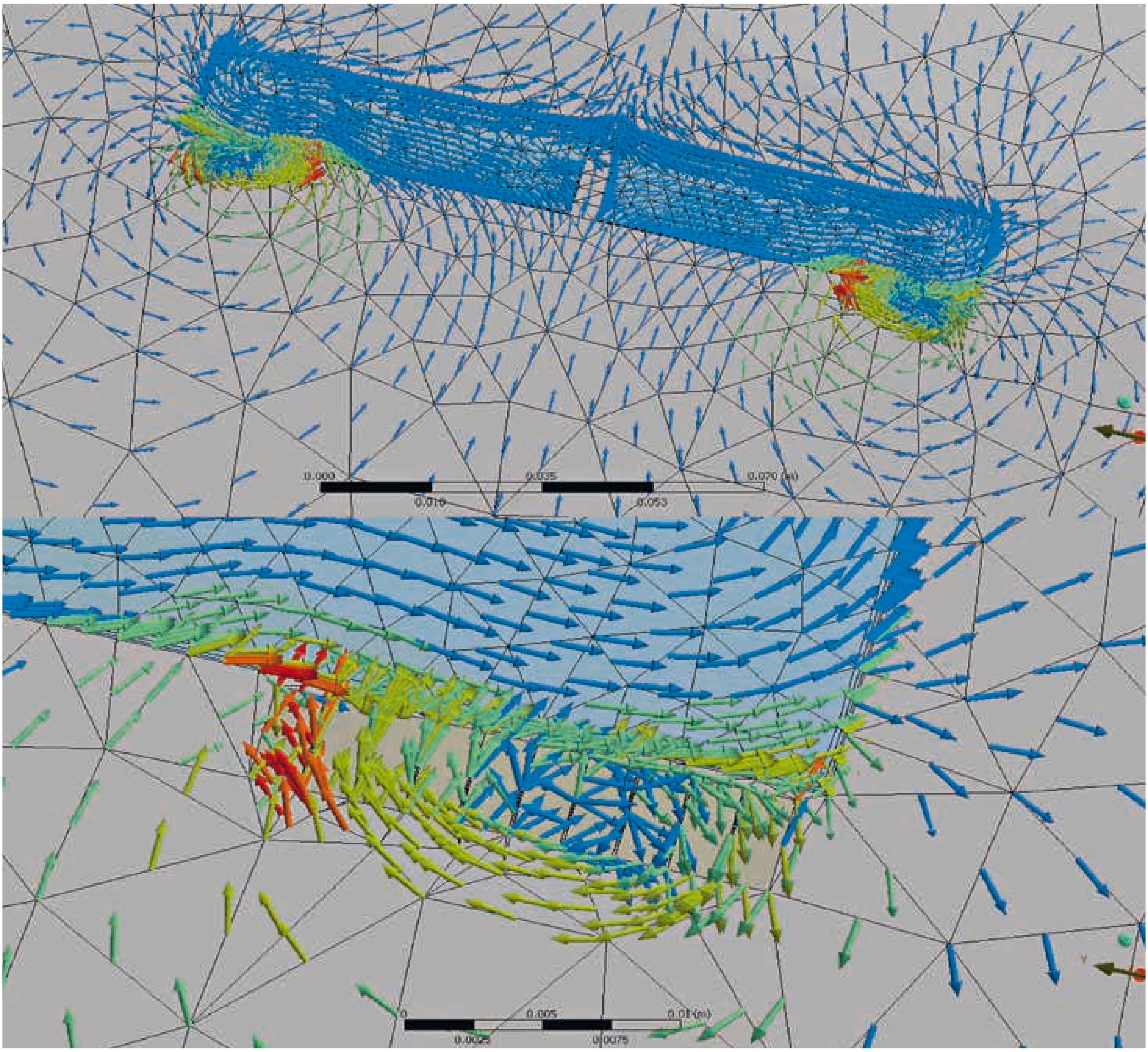
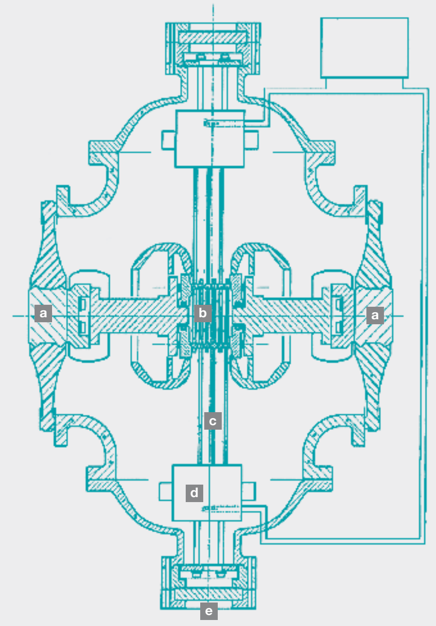


# Opening move

## 30 times faster than the blink of an eye, simulating the extreme in HVDC switchgear

DANIEL OHLSSON, JAKUB KORBEL, PER LINDHOLM, UELI STEIGER, PER SKARBY, CHRISTIAN SIMONIDIS, SAMI KOTILAINEN – One of ABB's most notable innovative achievements of recent times has been the development of the hybrid HVDC breaker. This breaker fills the last major gap on the road to HVDC grids and thus represents an important step toward increased integration of renewable power sources. The breaker itself and its significance and technology have already been presented in recent issues of *ABB Review*.[1] The present article takes a closer look at one of its core components – the so-called ultrafast disconnector, as well as the use of advanced simulation techniques in developing this highly critical and challenging part.

1 Metallic enclosure (patent sketch)



**a** Electrical leads (main circuit)
**b** Double-motion contact system (see also → 2)
**c** Movable insulation rods (see also → 3)
**d** Actuators
**e** Feedthrough and cables for actuators

Today, HVDC is mainly used for long-distance or subsea energy transmission. All links built so far are point-to-point connections, but the ability to interconnect links and ultimately form HVDC grids spanning large areas will strengthen the technology further. A major obstacle to such interconnections has been the absence of a suitable HVDC breaker.

> Fault currents in HVDC can rise rapidly due to low network impedances. An HVDC breaker must therefore be roughly 10 times faster than a comparable AC breaker.

The requirements on this breaker are high. Fault currents in HVDC can rise rapidly due to low network impedances. An HVDC breaker must therefore be roughly 10 times faster than a comparable AC breaker. A second challenge is the absence of the current zero-crossing exploited by AC breakers.

Addressing this need, ABB developed the hybrid DC breaker[2], combining semiconductor technology for rapid DC interruption with a fast mechanical switch (UFD, ultrafast disconnector).

## Ultrafast disconnector

The UFD has to be able to transition from carrying full current load to providing high-voltage insulation within a few milliseconds. It is designed as a high-voltage switch contained in a metallic enclosure → 1 filled with a compressed insulating gas. The two electrical leads → 1a to the switch are connected to the enclosure by means of bushings, which in turn are connected to an inter-

**Title picture**
Flux density distribution in intersection of coil and plunger in finite element simulation.

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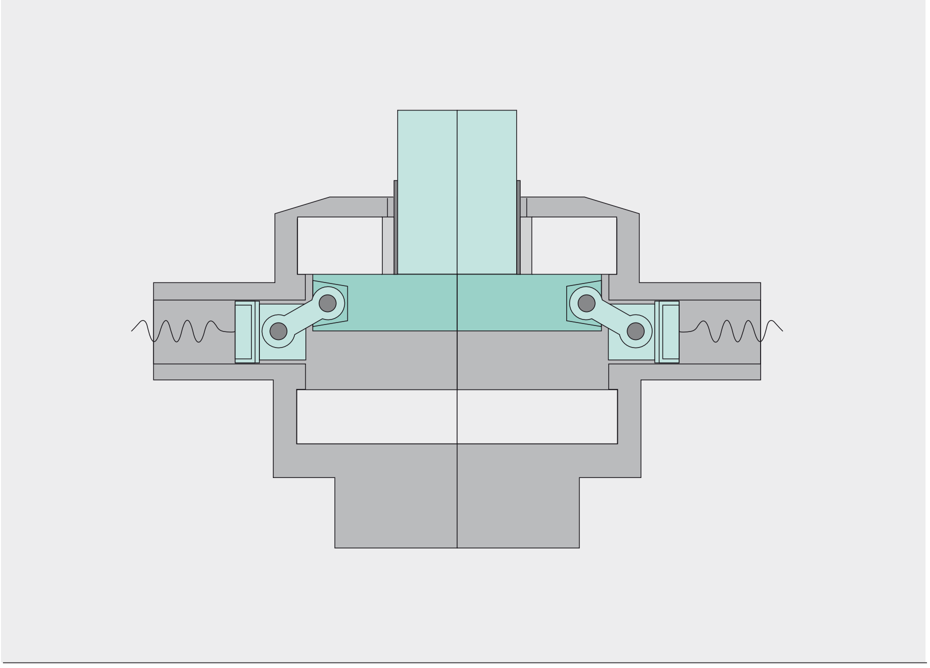
**Footnotes**

1 See also "breakthrough! ABB's hybrid HVDC breaker, an innovation breakthrough enabling reliable HVDC grids" *ABB Review* 2/2013 pages 6–13 and "Edison's conundrum solved" *ABB Review* 1/2013 page 6.

[2] See also J. Hafner and B. Jacobson, "Proactive hybrid HVDC breaker – a key innovation for reliable HVDC grids," CIGRE, Bologna Symposium, Sept. 2011, no. 264, pp. 1–9.

2 Cross-sectional view of the UFD's actuator showing the bi-stable spring arrangement



The UFD has to be able to transition from carrying full current load to providing high-voltage insulation within a few milliseconds.

nal current path supported by insulators. The active switching elements consist of a high-speed double-motion contact system ➔ 1b.

The contact system is multisegmented and embedded in movable insulating rods ➔ 1c. These insulating rods are in turn connected to electromagnetic actuators of repulsive force type based on the Thomson coil principle ➔ 1d and ➔ 2. This actuation principle allows a very high and nearly instant acceleration of the connected contacts. The actuators operate in a direction perpendicular to the current path and have their opening and closing coils connected in series to one another to ensure a synchronous motion. The actuators have a bi-stable spring arrangement to ensure that the closed and open positions are well defined. They are fully integrated within the enclosure and connected to a separate energy storage unit by means of gas-tight feedthroughs and cables ➔ 1e.

## Multiphysics

The simulation of a circuit breaker requires modeling of several physical domains. Some of these can be treated as decoupled; ie, they have no significant influence on each other (eg, electrical field stress and mechanical stress). Other domains interact strongly (multiphysics). This article looks chiefly at the interactions between mechanics, gas physics and electrodynamics.

## Modeling approach

Different simulation approaches can roughly be split into two main fields, finite element (FE) models and lumped models. The FE approach (where the geometry can be captured in detail) is the most accurate. Often, lumped models (also called integral models) are good enough to describe the system. They have significantly shorter simulation time (seconds instead of hours, or even days). Lumped models require more effort when it comes to model development, since everything has to be simplified and adapted accordingly. FEM physics on the other hand require element formulation and the main effort lies in construction and meshing of the model. Picking the suitable method is typically a trade-off between simulation time, accuracy and modeling time.

## Mechanics

The mechanical simulation model of the ultrafast disconnector consists of roughly 50 parts. Based on their CAD geometry, an optimal and efficient mesh of each part was created. The size of the model reached about 150,000 elements with 200,000 nodes. The mesh was refined at the contact surfaces. Due to the high-speed operation and the complex contact interactions between the individual parts, an explicit time integration method was chosen. This resulted in overall simulation times in the order of several hours.

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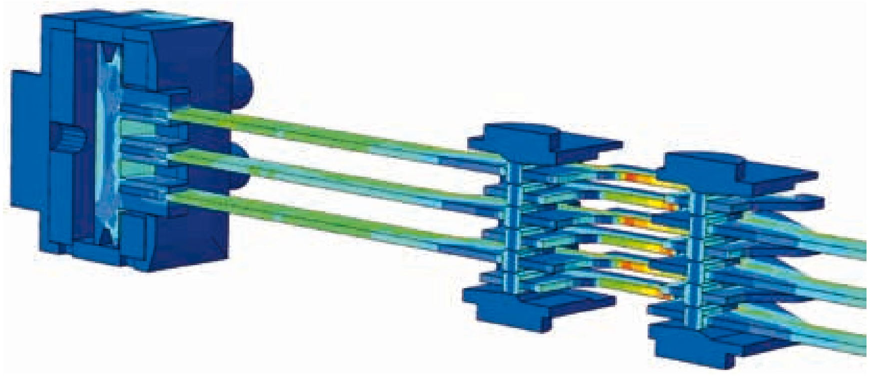
3 Stress state during the acceleration phase of the mechanism



As a first step of the simulation, the pretensioned springs and bolts are set to an initial state. In the second step the Thomson coil load is applied as an induced force onto the area of the armature that faces the coil. On the opposite side of the armature facing the travel direction, a damping force is applied depending on the speed and position of the armature.

Simulations permit quantities such as strains, contact pressures as well as displacements, velocities and accelerations to be studied, evaluated and visualized.

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## Gas damper

After the contact system has been accelerated to a high velocity, it must be decelerated in a very short distance.

A good way of dissipating the kinetic energy is to use a gas damper. It has a high power density, no moving parts and low space requirements. Since the UFD drive is contained in pressurized $SF_6$, this gas can be used. The damping force is achieved by generating a gas pressure. The challenge is to achieve the stopping of the motion without impact or bouncing ➔ 4.

The correct dimensioning of a gas damper requires an iterative process. Since the requirements during product development can change, the work has to be redone several times. Therefore the lumped model approach was chosen for modeling the gas damper.

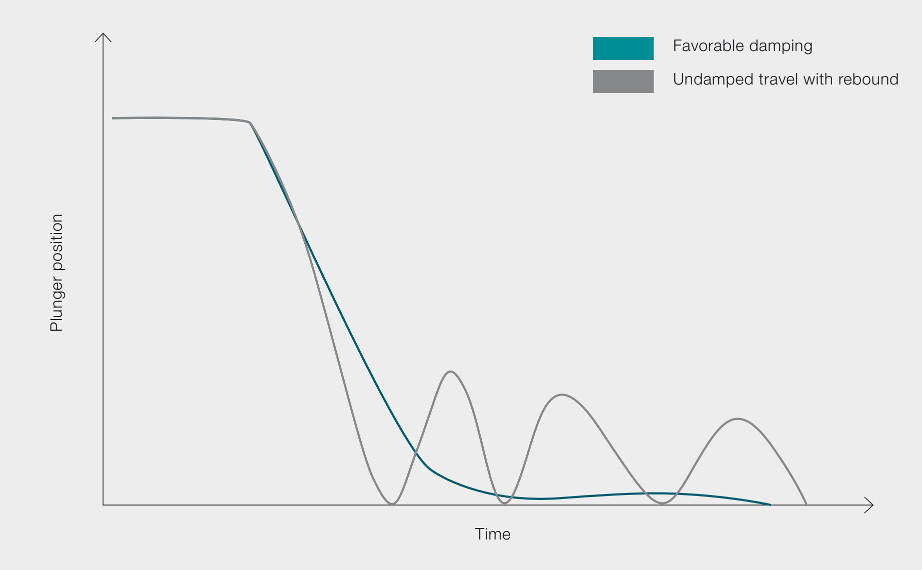
One big challenge for the design was to get good damping for both opening and closing operations without dissipating energy during acceleration.

In the dimensioning of the damper, multi-objective optimization methods were used to identify trade-offs between Pareto optimal designs. It was then possible to pick the most favorable compromise depending on the requirements.

## Thomson drive

The Thomson effect uses the mutual inductance between two electrical conductors. These create a strong time-variant magnetic field causing a repelling (Lorentz) force between the conductors when a brief but strong short-circuit is applied ➔ 5.

4 **Desirable and undesirable damping properties**



One big challenge for the design was to get good damping for both opening and closing operations without dissipating energy during acceleration.

The principle function of a Thomson-coil actuator is to discharge a capacitor into an electrical coil that induces eddy currents into an aluminum plate. This leads to a repelling Lorentz force between the coil and plate, accelerating the mechanism connected to the plate.

In order to simulate the coupled electromagnetic-thermal-mechanical physical problem, two approaches with different focuses are adopted. Three-dimensional finite-element analysis is applied with electromagnetic models to capture detailed transient magnetic and electrical field effects (including thermal processes) but only a simplified lumped model of the moving plate. Solving visualizes the diffusion process of the magnetic field, time-variant eddy current and related losses.

The simulation of a circuit breaker requires modeling of several physical domains.

In addition to the computationally costly finite element analysis, a simplified lumped model of the electro-thermodynamic system was created to enable co-simulation with more complex structural mechanics models. The complex magnetic equations are thus reduced to ordinary differential equations, which are coupled through mutual inductance. This is a simplification of the partial differential equation problem down to static electromagnetics.

## Co-simulation

The previously described simulation models were coupled in co-simulation in order to solve the complete problem simultaneously and capture mutual influences. A coupling routine exchanges state variables between the software packages ➔ 6. Since the entire analysis takes just 10 ms, a coupling step of 0.01 ms was chosen to achieve numerical stability and low information loss.

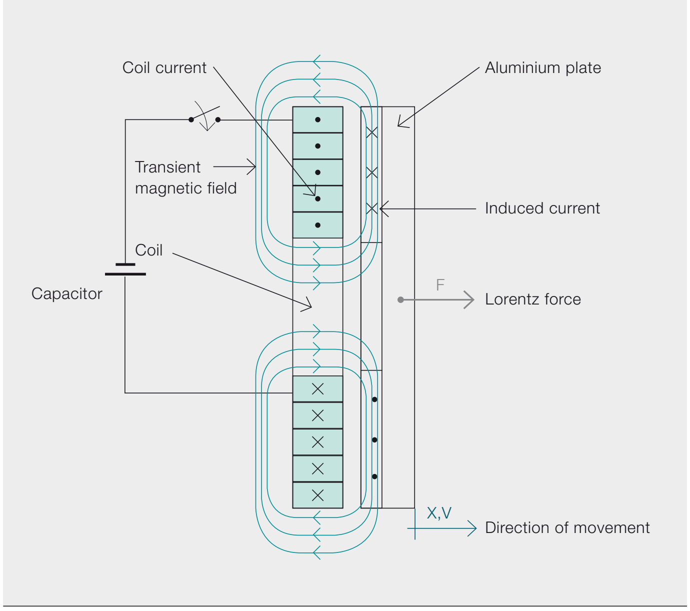
### Actuation

Within the electromechanical coupling, the interfacing variables are the electromagnetic actuation force and the position of the plunger. The lumped electromagnetic model computes the actuation force acting on the plunger and hands it over to the FE model at every communication step. The FE model computes acceleration of the plunger and the distance between the plunger and coil. The position state is similarly returned to the lumped model at every communication step, enabling accurate prediction of the movement.

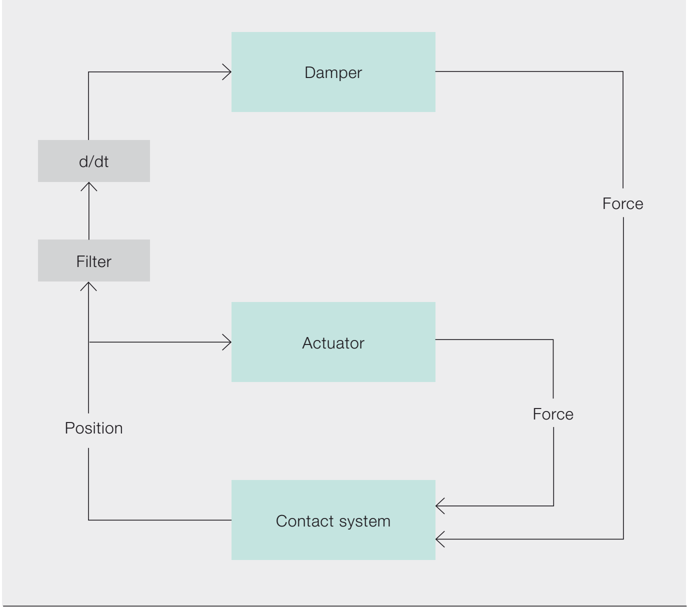
### Damping

Within the fluidic-mechanical coupling, the interfacing variables are damping force and damper position. The FE model provides the damper position states at

5 Schematic outline of Thomson-coil arrangement and electromagnetic fields



6 Co-simulation flowchart



> The Thomson effect uses the mutual inductance between two electrical conductors, creating a strong time-variant repelling (Lorentz) force between the conductors.

each communication step. The lumped fluid-dynamics model transiently computes pressure and volume relations and returns the damping load on the related part back to the FE model.

## Measurements

The laser-Doppler vibrometer (LV) is a precision optical transducer used for determining vibration velocity and displacement at a fixed point. LV measurements are applied to the mechanical DC breaker in tests. Experiments are performed in an $SF_6$-filled enclosure where the laser is directed through a view port, and position and velocity can thus be obtained with high precision, identifying even structural movements of individual parts in the kinematic chain.

An example of experimental recording of position and velocity using LV is shown in ➔ 7. Although no filter was applied, the curves are smooth. The velocity curve ➔ 7b allows for identification of oscillations in the higher frequency range that visualize structural vibrations ➔ 8. The extreme velocity change shown in ➔ 7b illustrates the huge acceleration forces acting on the system.

## Results/validation

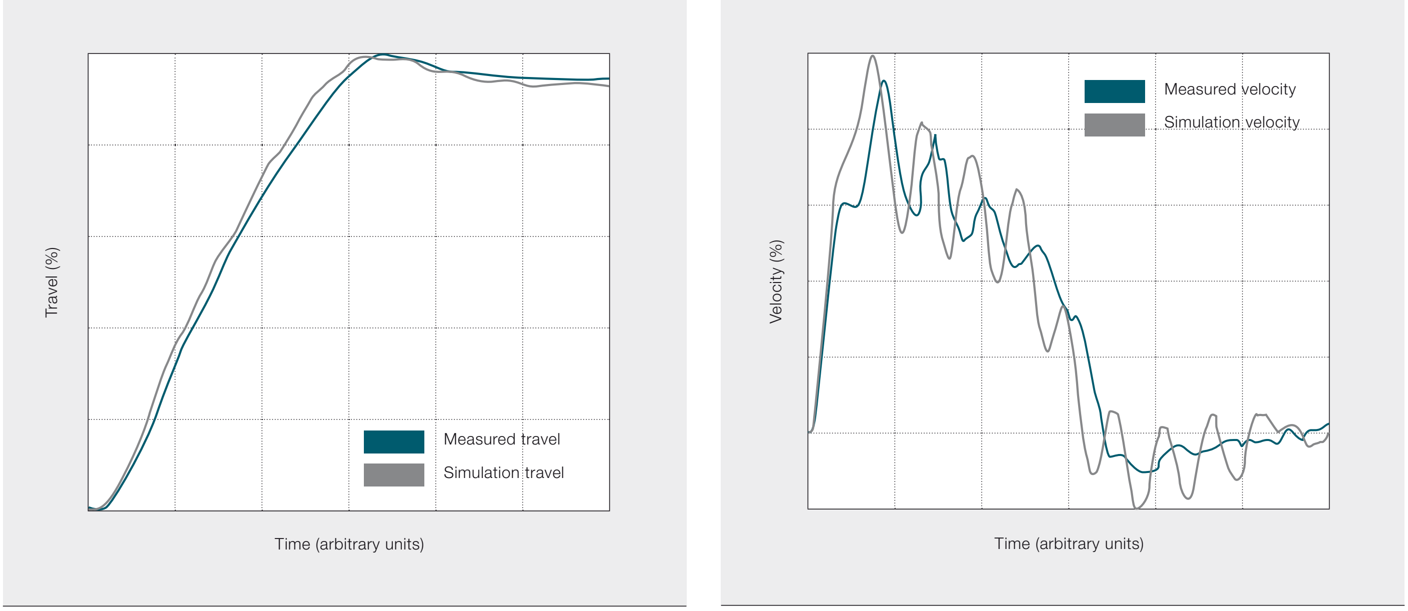
Most of the work performed on the simulations was to reduce the impact of the contacts: The simulation tool was of great help in visualizing the impact behavior.

From a mechanical point of view is the connection between moving parts is critical. Since all loads were included in the co-simulation, the possible failure locations were identified and the design was improved in order to avoid such problems.

## Successful simulation

Advanced simulation tools that combine domains from several engineering disciplines have become indispensable in today's fast-paced product development. The ubiquity of powerful computational resources has enabled simulations at a much higher fidelity level to be pursued than previously possible. Not only can these tools complement experimental work based on physical pro-

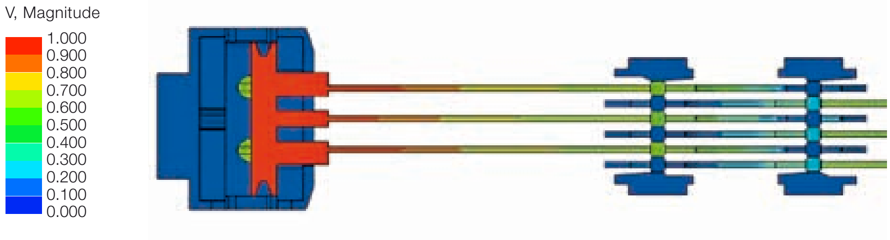
7 Comparison of computed travel curve with the tests results:



**7a Travel**

**7b Velocity**

8 Velocity magnitude – demonstration of wave propagation in the system



> The complex magnetic equations are reduced to ordinary differential equations, which are coupled through mutual inductance.

totypes, but they also enable exploration of a much larger design space. Once the required model fidelity has been defined and sufficiently good correlation between experimental measurements and simulation results obtained, a third step can include numerical optimization of the simulation models where the design variables can be driven simultaneously toward multiple objectives. As the products in the electrical and automation industry become more and more multidisciplinary, combining electrical, mechanical and computational features, advanced simulation tools will certainly play an ever larger role in their development.

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