ABB review

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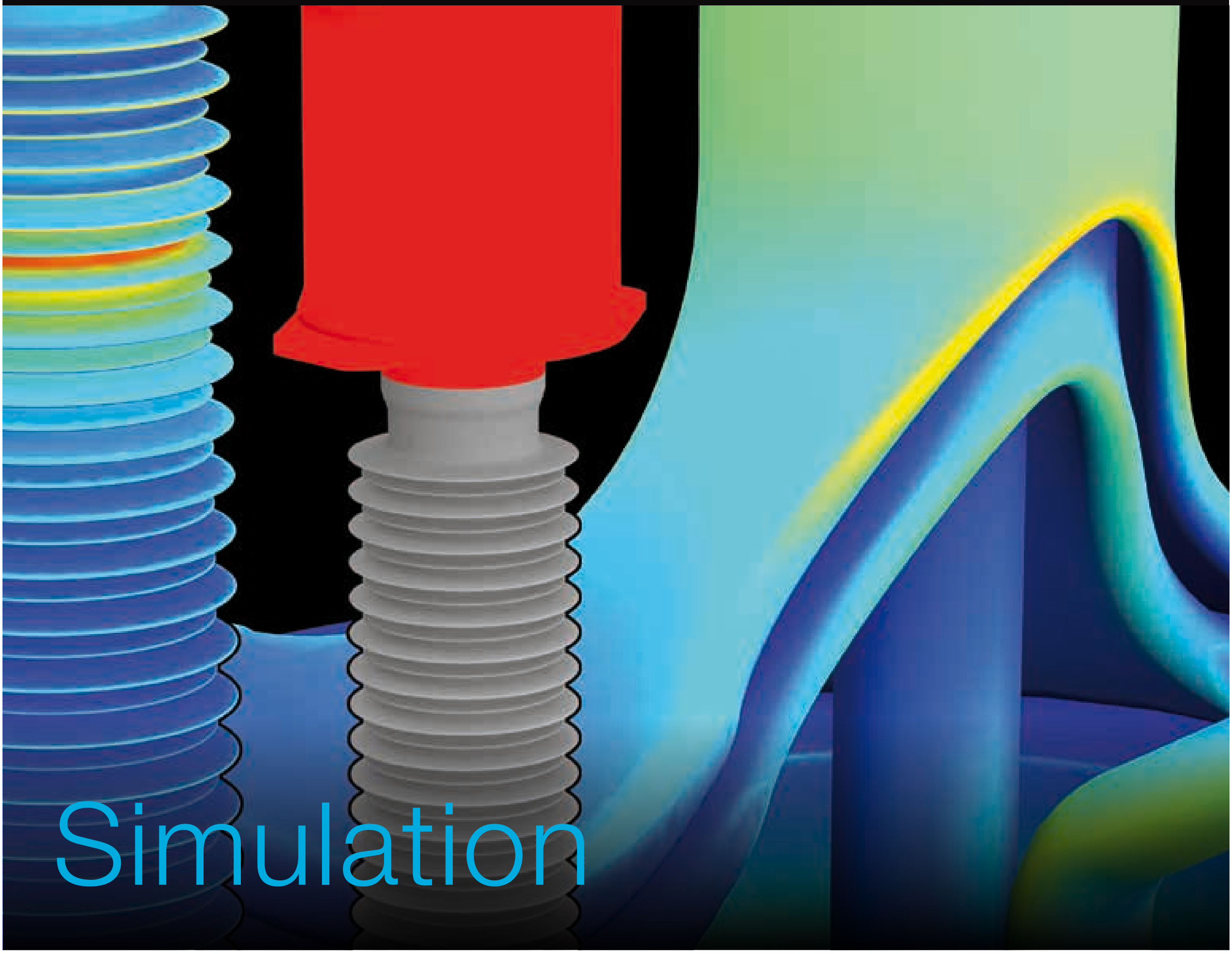
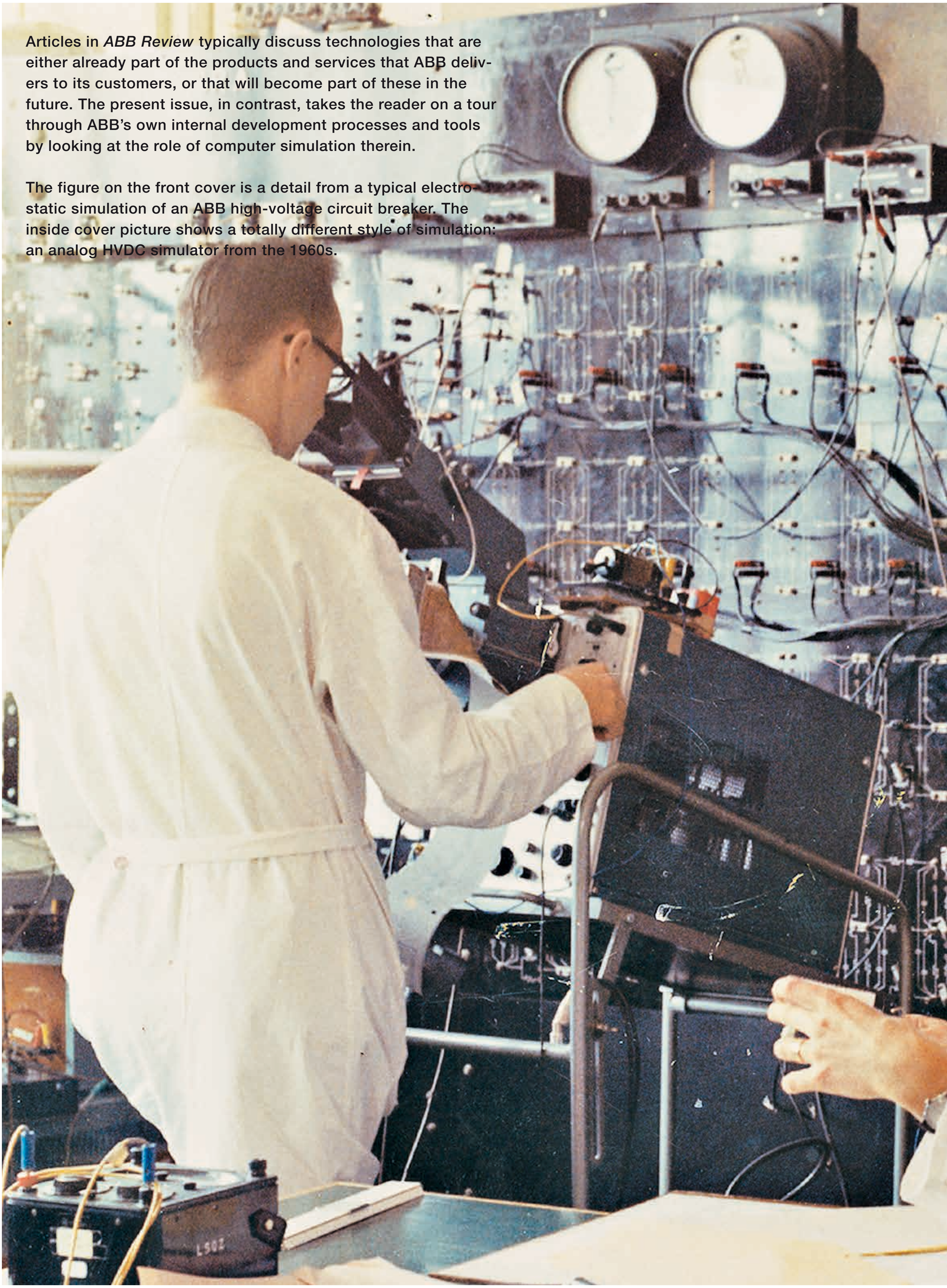
The corporate technical journal



Simulation

Power and productivity for a better world™



Articles in *ABB Review* typically discuss technologies that are either already part of the products and services that ABB delivers to its customers, or that will become part of these in the future. The present issue, in contrast, takes the reader on a tour through ABB's own internal development processes and tools by looking at the role of computer simulation therein.

The figure on the front cover is a detail from a typical electrostatic simulation of an ABB high-voltage circuit breaker. The inside cover picture shows a totally different style of simulation: an analog HVDC simulator from the 1960s.

World of simulation

Energy simulations

Movement, pressure and control

Simulation

Claes Rytoft

Dear Reader,

Computer simulation plays a crucial and growing role in product development. With every product generation surpassing its predecessor in terms of complexity and optimization, it is increasingly important for engineers to gain deeper understanding of the physical effects that limit performance. Such detailed understanding cannot be gained by testing alone, especially not within the time and economic constraints that the market allows. Furthermore, by permitting the comparison of additional design variants and the exploration of what-if scenarios, confidence in the selected configuration is strengthened and the customer is assured of an optimal solution.

The most sophisticated of simulations is of little value if its margin of accuracy is not correctly understood by the recipient of the information (we have all experienced the frustration that can result from placing too much trust in an over-optimistic weather forecast). Besides drawing on a broad range of scientific fields, simulation has evolved into a discipline in its own right. Simulation engineers must be able to answer such questions as: Does the underlying model adequately describe the phenomenon being simulated? How fine must the mesh and time resolution be for the results to be sufficiently accurate? Which simplifications are acceptable and which are not? It is remarkable to note that the reliability of simulations has now reached the point that standards committees such as the IEC accept simulations as an alternative to testing for certain criteria.

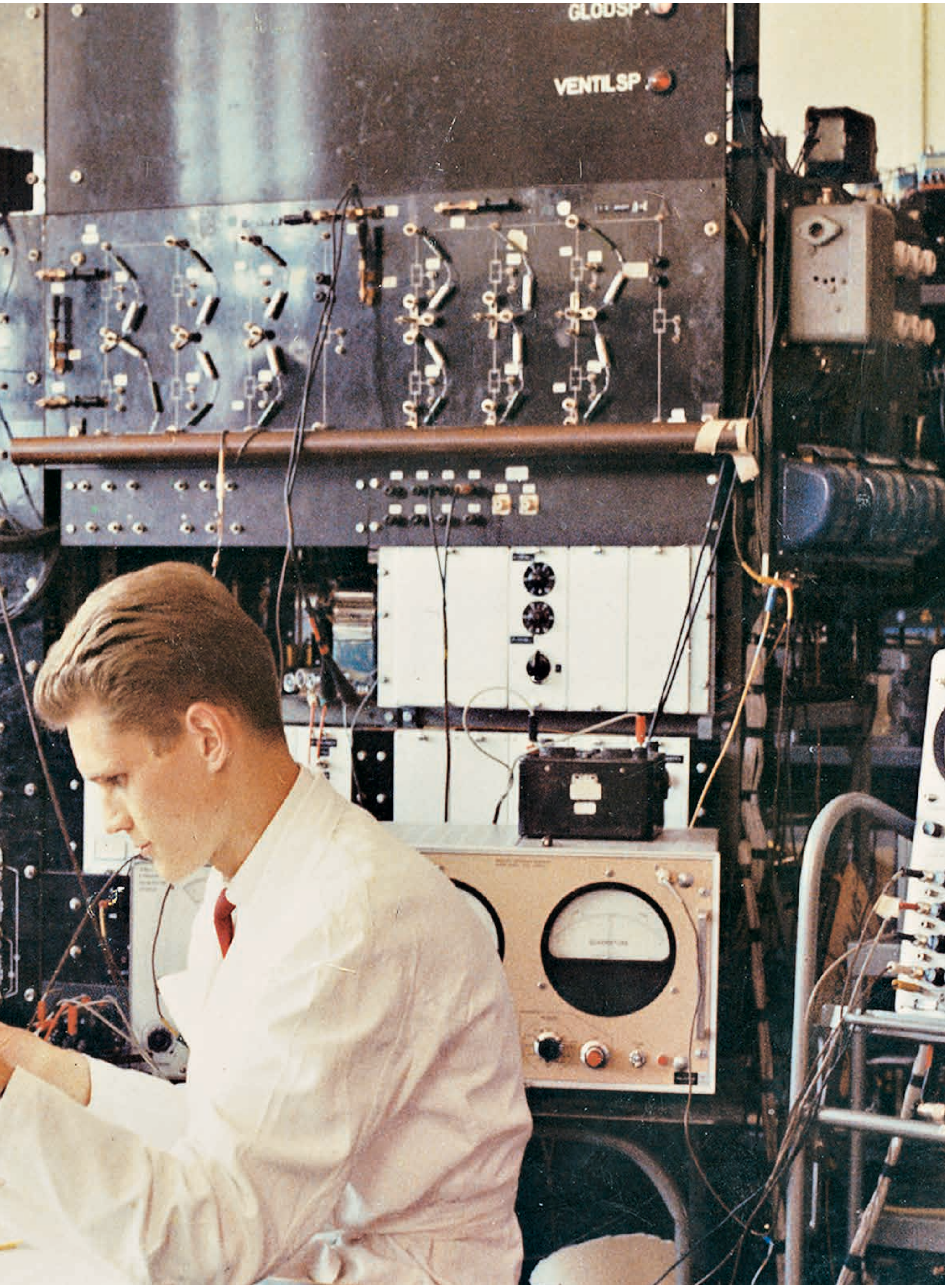
One important challenge in simulation is the interaction between different physical phenomena in what simulation engineers call multiphysics. In a current breaker for example, electromagnetics, thermodynamics, fluid dynamics and mechanics all affect one another. Simulation must thus deal with all these effects and their interactions.

This issue of *ABB Review* unites a remarkable spread of simulation applications ranging from large transformers to integrated electronics. The simulations discussed deal with timescales ranging from ultrafast switching actions to lifetime wear and tear, and even to the casting and curing of materials during manufacture.

In an issue on simulation, it is appropriate to also advance the virtualization of *ABB Review*. The previous issue announced the launch of an email alert to keep readers informed of new issues. Going one step further, we are now also launching a tablet version. Information on both of these can be found on page 83.

Enjoy your reading.

Claes Rytoft
Chief Technology Officer and
Group Senior Vice President
ABB Group

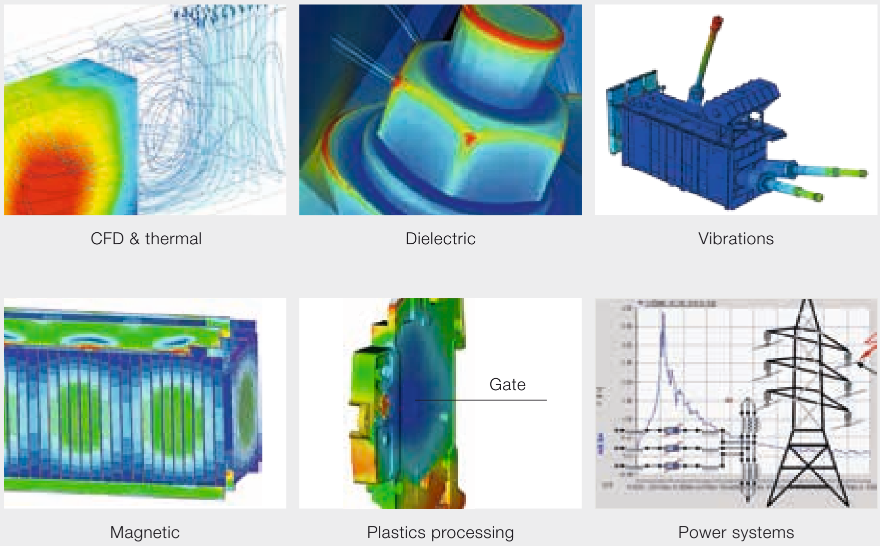

GLODSP.
VENTILSP

Reality predicted

Simulation power for a better world

GEORG SCHETT, MAREK FLORKOWSKI, ARTHOUROS IORDANIDIS, PETER LOFGREN, PIOTR SAJ – Simulations play a pivotal role in today's research and engineering work. Advances, both in computer power and computational techniques, are constantly expanding the range of simulation applications as well as their accuracy. The scope of applications ranges from multiphysics through system study to manufacturing and production processes. Most of the cases discussed in the present issue of *ABB Review* are concerned with computing spatial and temporal distribution of physical quantities such as electromagnetic, flow and temperature fields. This article looks at some of the principles involved.

1 Examples of types of simulation areas and tools



The main purpose of simulations in engineering design is to understand phenomena taking place in a real physical object or system and to optimize the design process → 1. The overall process starts with the digitization of the real object and ends with implementation of the digital information gain in design changes → 2.

Simulation methods

There are many different methods of performing simulations:

- Mesh based (geometrical discretization)
- Meshless
- Systems and networks studies
- Production process analyses
- Others

Mathematical modeling

Mathematic modeling is the first step in a computer simulation. In this phase, the physical problem is described in terms of mathematical equations. Only the physical phenomena described by the equations can be captured in the simulation. The challenge of mathematical modeling is to find a balance between the complexity of the real system and the engineering rationale required for the application of the model in product design. Correct mathematical description of the physical phenomena is a subject of theoretical (or mathematical) physics – a scientific field in the overlap of physics and mathematics.

Preprocessing

Preprocessing is the step of preparing the geometry for simulations. This is another idealization step in which the geometry is simplified to the point that, on the one hand it retains the relevant geometrical features, and on the other allows the generation of an appropriate mesh. From this point onward the real geometry is replaced by a meshed geometry. Creation of a high-quality mesh is one of the main bottlenecks in the industrial application of simulations. Indeed, real industrial geometries are typically very complicated and not easy to cover adequately by a computational mesh. Moreover, if the created mesh has a poor quality, it will likely hinder the convergence of the simulation or lead to physically incorrect solutions.

Solution

The equations of the mathematical model are solved numerically on the computational mesh. The discretization method transfers the model equations from the continuum to the discrete domain. Finite and boundary element methods (FEMs and BEMs, respectively) are typically used by ABB for mechanical and electromagnetic computations, whereas finite volume methods (FVMs) are common for computational fluid dynamics (CFD). These are the methods most commonly used in ABB's computational methods for field calculations, but numerous commercially available and academic tools based on other discretization methods do also see use. It is also common that technology companies (such as ABB) develop dedicated computational methods and solvers for their specific engineering needs[1].

Post-processing

Post-processing is the phase of visualizing the obtained results and is an integral part of the simulation process. In general, it involves visual presentation of simulation results, usually in the form of a 2-D or 3-D map (contours) showing the distribution of a quantity obtained from the calculations. Dynamic behavior of the simulated object or process can be visualized by animations. Such a spatiotemporal presentation of the computed physical quantities makes simulations particularly suited and attractive for analyzing complex physical phenomena in real devices. However, besides the field visualizations, presentation forms such

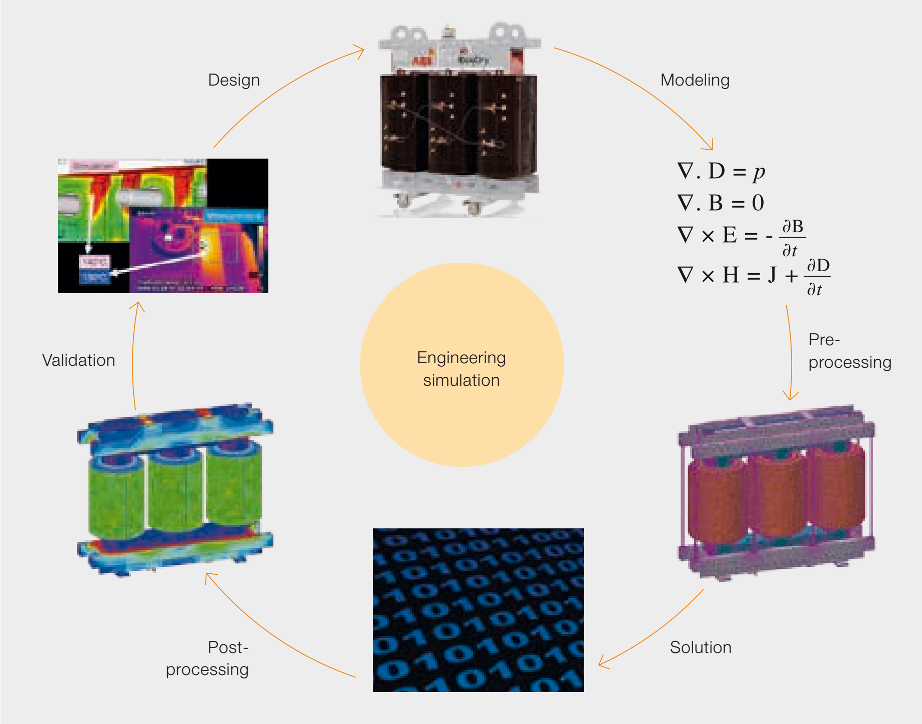
Title picture

Simulation plays a vital part in the design and development of new products. The title picture shows the assembly of corona shields in ABB's UHV (ultrahigh voltage) test hall in Ludvika, Sweden.

Footnote

1 See also "Simulation toolbox: Dielectric and thermal design of power devices" on page 16 and "Switching analysis: Simulation of electric arcs in circuit breakers" on page 34 of this edition of *ABB Review*.

2 Schematic representation of a simulation process cycle



as point plots and time-space averaged quantities are also of great importance since they can be directly compared to the measurements. Recent rapid growth in digital 3-D imaging technologies has also opened new capabilities for visualization of computational data.

Validation

The relative simplicity of gaining a comprehensive insight into complex physical phenomena by simulation exposes its main pitfall: Simulations can return false results bearing no relevance to the real physical phenomena, or so-called "nice colorful pictures" with incorrect or even misleading information. Such spurious solutions can be a result of deficiencies at every step of the simulation process: the wrong model, oversimplified geometry, inaccurate material data, an inappropriate mesh and an inappropriate solver.

To assure the match between the simulated results and real physics, a validation should be conducted. This final check is normally achieved by comparing the computed and experimental results. The process of validation is complicated by the limited number of parameters that can be measured directly. In spite of the difficulties, the validation step is mandatory, since validated simulations are distinguished by their predictive power (this is in contrast to calibrated simulations, where the validity of the results is always questionable outside the range of calibration).

Design

Finally, the simulation loop is closed by extracting information from the simulations and making design changes based on the data. At this stage the tremendous potential of simulations can be exploited to facilitate product development. First of all, simulations provide understanding of the details of the physical phenomena, and are hence of great importance for the designers. Additionally, simulation results can be obtained much faster than prototype building and testing. A great strength of simulation lies in the ability to perform parametric studies that replace expensive trial-and-error loops in classical design processes.

Simulation at ABB

ABB, as a leading technology company, has introduced a variety of simulations into its research and development activities.

A good example is the short-circuit testing of the largest ABB step-up transformers. It is critical that such a transformer can withstand the electromagnetic forces originating from the high short-circuit currents. Due to the very high energies involved, there are only few facilities in the world where such transformers can be tested. The challenge is augmented by the very large dimensions of these transformers that impose severe constraints on their transportation. Obviously, such testing is associated with very high costs and time requirements. It is remarkable to note that recent progress in simulation has led to changes in international standards, making it acceptable to demonstrate short-circuit withstand capability through computations (IEC 60076-5).

Another example of advanced coupled field simulations – providing an extraordinary insight into the physical phenomena taking place in the device – are arc simulations in circuit breakers. The circuit breakers are designed to withstand and interrupt short-circuit currents of up to hundreds of kA within tens of ms. Testing these is not only costly and time consuming, but the number of measurable parameters is also very limited. ABB can run coupled electromagnetic / fluid dynamic / mechanical simulations to capture the true behavior of the breaker during fault current interruption[2]. As a result of the simulations, the designers obtain full insight into the flow conditions in the breaker. They can measure the pressure and voltage at any point within the breaker and can compute forces acting on the critical components. This is a powerful technique, enabling the emergence of

Advanced and complex simulations of multi-physical phenomena occurring in breakers, transformers, motors, drives, robots, electrical power systems and many others are carried out routinely at ABB. The globally distributed experts contribute onsite to both speed up the development phase and minimize the expensive testing effort.

breaker designs of even greater reliability. Finally, almost all ABB products deal with voltages. Although at the lowest voltage levels, dielectric insulation can be handled by simple design rules, at high voltages design work is virtually impossible without calculations of the electric field. Therefore, 2-D and 3-D electric field computations are indispensable parts of the design process in many ABB development processes.

Use of such tools reduces the dielectric stress on the critical parts of products and thus avoids breakdowns and failures. Until recently, such computational investigations have been done by running a set of simulations in order to select the best parameters from this often limited set. Today, due to the progress in optimization methods and computing power, optimal solutions can be found by combining electric field computation with an automated optimization. Such advanced methods have already been integrated into ABB design tools such as Simulation Toolbox and are revealing their huge potential[3].

Due to the importance of simulation and its rapid growth in ABB's research and development efforts, global internal simulation conferences have been organized within the company in order to share experiences and best practices. At these events, ABB has also learned from the leading companies within related industries such as automotive, aircraft and consumer industries.

With the skills and experience acquired, ABB has further optimized its simulation environment by:
- Making core simulation tools easily accessible to all engineers
- Sharing simulation clusters for large and CPU-intensive simulations
- Holding virtual forums for sharing best practices
- Providing simulation support for less experienced development teams

Today ABB can confidently assert that it is in a strong position when it comes to applying simulation and using it to develop the best products for customers. This issue of ABB Review reports on a wide range of advanced simulations ranging from electromagnetic effects in transformers to the processing of plastics.

Future simulation trends

The progress in simulation was made possible by progress in software and hardware, mainly processors, storage and communication. In the past, highly complex simulation could be run only on supercomputers or big clusters, whereas more and more frequently high-power desktop computers are sufficient today. The computing power of supercomputers will soon be measured in exaFLOPS, and high-performance notebooks can today already reach already the level of terraFLOPS – a magnitude that was hard to imagine as little as a decade ago. Simultaneously, due to new graphics processors, an enormous development can be observed in post-processing and visualization including the animation of results. This trend is continuing, as can be observed for example in the incredible computational power of today's mobile devices. Cloud computing is maybe still in its incubation stage, but in the near future complex simulations will be started from desktop or mobile devices and calculated somewhere in the cloud.

Future areas of simulation are unlimited, going beyond new designs, system study and production optimization. One can imagine in the near future that on-site simulations could be based on mobile services, that full parametric multiphysical optimization will be possible, or even 3-D printers equipped with simulation and optimization modules to recalculate objects on the fly prior to printing.

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Footnotes

2 See also "Switching analysis: Simulation of electric arcs in circuit breakers" on page 34 of this edition of *ABB Review*.

3 See also "Simulation toolbox: Dielectric and thermal design of power devices" on page 16 of this edition of *ABB Review*.

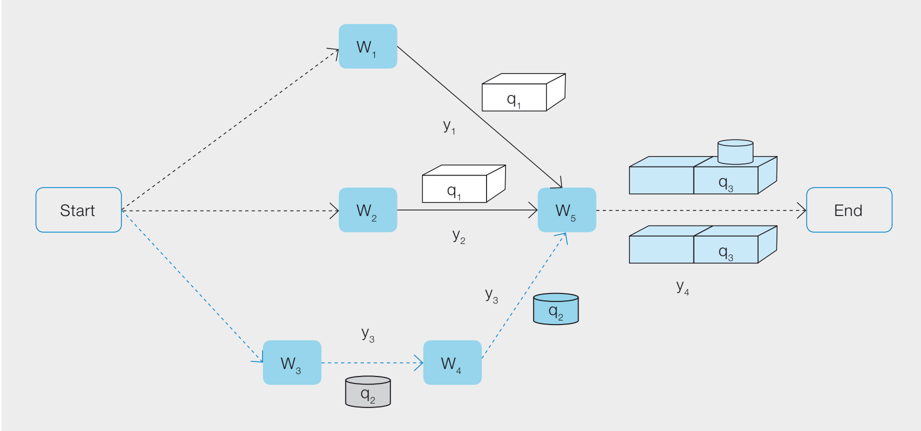
Reordering chaos

Applied mathematics improves products, industrial processes and operations

LUCA GHEZZI, ALDO SCIACCA – In a world of finite resources and an almost infinite number of binding constraints, mathematical modeling and simulation tools help optimize complex systems. Applied mathematics brings a rational outlook, precise problem definition and representation, qualitative and quantitative prediction capabilities, and the possibility to simulate how stochastic properties or unpredictable external forces affect system performance. Applied mathematics can yield significant savings in industrial processes and manufacturing as well as in the world of operations, such as in distributive logistics, production planning and sales force organization.

Title picture
For over 70 years, mathematics has been used to find optimal solutions to multivariable problems. The same techniques can also be used in factory settings to identify cost-effective production strategies.

1 A schematic representation of a simple production line, in the form of a directed graph



As frequently happens, wartime brings leaps in technology and science. Thus operations research (OR) and its main tool, mathematical programming (MP), blossomed during the dramatic years of World War II. Then, the idea was to use mathematics to solve literally life-saving problems such as where to locate the first few, and expensive, radar installations to spot and counter aerial offenses coming from the continent. A new method was needed to optimize a goal function that maximized the territory covered by the radar, bearing in mind physical, economic and integrality constraints – for it was not possible to locate one-quarter of a radar in Dover and the other three-quarters in Folkestone. The same techniques were used to determine the optimal size and composition of North Atlantic supply convoys.

The number of topics tackled by OR has become progressively larger – including combinatorial optimization problems that are constrained by equalities and inequalities and that function with continuous or discrete variables. Industrial processes, logistic networks, sales organization, scheduling and most other aspects of large organizations teem with examples of situations that can be optimized by an appropriate application of OR.

Mathematical programming

The mathematical response to the issue of combinatorial complexity is called mathematical programming, where a "program" is the problem of minimizing a goal function f(x,z), subject to equality and inequality constraints g(x,z)=0, h(x,z)≤0, with real (continuous) and/or integer (discrete) variables. Robust approaches exist for those programs of a convex nature, for which the existence and uniqueness of a solution may be assumed in advance.

The art of modeling consists of reducing complicated problems to as-simple-as-possible mathematical formulations that, nonetheless, retain the essence of the problem.

The art of modeling consists of reducing complicated problems to as-simple-as-possible mathematical formulations that, nonetheless, retain the essence of the problem. For example, in a simple production plant, the goal function is typically the profit. This is a linear function of the product quantities sold and production costs, which latter, in turn, depend linearly on production quantities → 1. The market requires a minimal quantity of products, which requires minimal quantities of subproducts, and so on down to raw materials, with each stage passing a minimal quantity constraint on to the next. At each work station in the process, the cumulative machine time required is constrained from above by the available machine time. Some stations require manpower to be drawn from finite capacity reservoirs (with due competence specialization constraints), which pose further inequality constraints. Intermediate buffers and warehouses can form dynamic item storage pools, to be depleted or increased, with lower bounds (safety margin against stockout), upper bounds (capacity) and additional cost contributions.

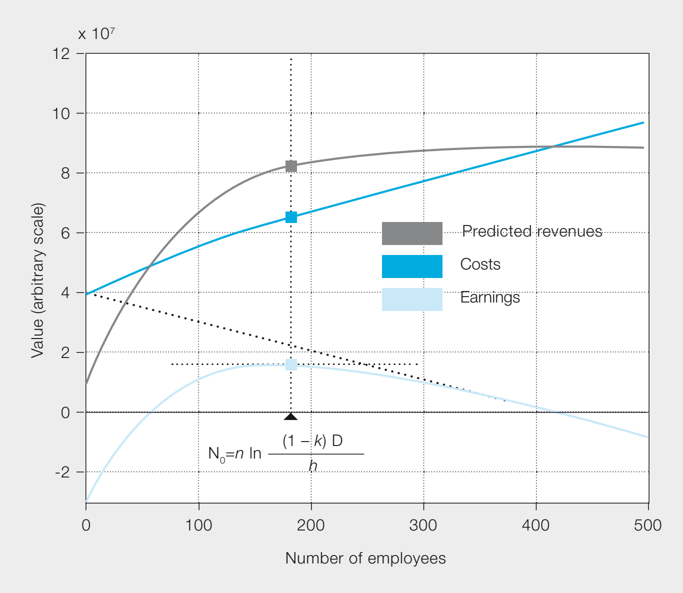
All this can be made into a convex program and MP will deliver an optimal management strategy. A large collection of building blocks, with thousands of variables and linear constraints, allows a complete production line, or even a factory, to be modeled, inclusive of outsourced stages. Indeed, this very exercise was performed for ABB's electric motor plant in Vittuone, Italy.

Graph theory

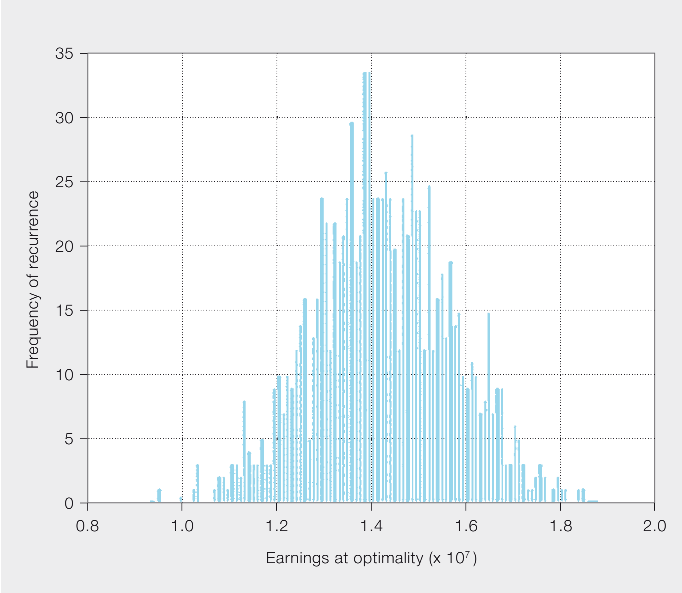
As can be seen in the example above, a graph offers a clear, ordered, intuitive and visual representation of the problem to be solved. Indeed, graph theory is a major OR tool, for solution purposes as well as for representation.

From the graph theory standpoint, all arbitrary systems represented by nodes and connections may be treated the same. Therefore, a distribution logistics

2 A simple approach yields results



2a Predicted revenues (grey), costs (blue) and earnings (light blue) vs. sales force, with optimal sizing



2b Propagation of variance over earnings in a sample, illustrative case

network or a supply net can be graphically modeled in the same way as a production plant. Customers to be served, transit points, logistic hubs, warehouses and production equipment are the graph nodes, while admissible routes are the connecting lines. Capacity constraints affect transport, handling operations and production. Market demands pose lower bounds for goods dispatched (others go to warehouse inventory) and everything is given a cost.

Many canonically formulated MP problems for network optimization equate to classical graph theory problems, for which simple but powerful theorems yield exact solutions – directly and without too much number crunching.

Part of the ABB logistic network in Italy has been simulated in this way in order to find an optimal management strategy.

Heuristics

Often, computing an exact solution takes too long. Further, data is often intrinsically uncertain and mutable, and a safety margin is usually needed in any case. Therefore, a suboptimal solution may often be a more reasonable option.

Based on different approaches, such as the application of sequences of improvement rules or the imitation of physical, human or biological system evolution, heuristics are discovering methods that lead to a solution that is not necessarily the optimum but is frequently acceptably close to it. Sometimes, the clue for a proficient heuristic method can come from pure mathematics.

For instance, by following, in a heuristic fashion, the very same steps as the celebrated Euclidean algorithm for the greatest common divisor of integers, it is possible to sequence a collection of different items belonging to some given families, such as products to manufacture in a production plan, to try to maximize their scattering (interestingly, here more chaos is sought, rather than less).

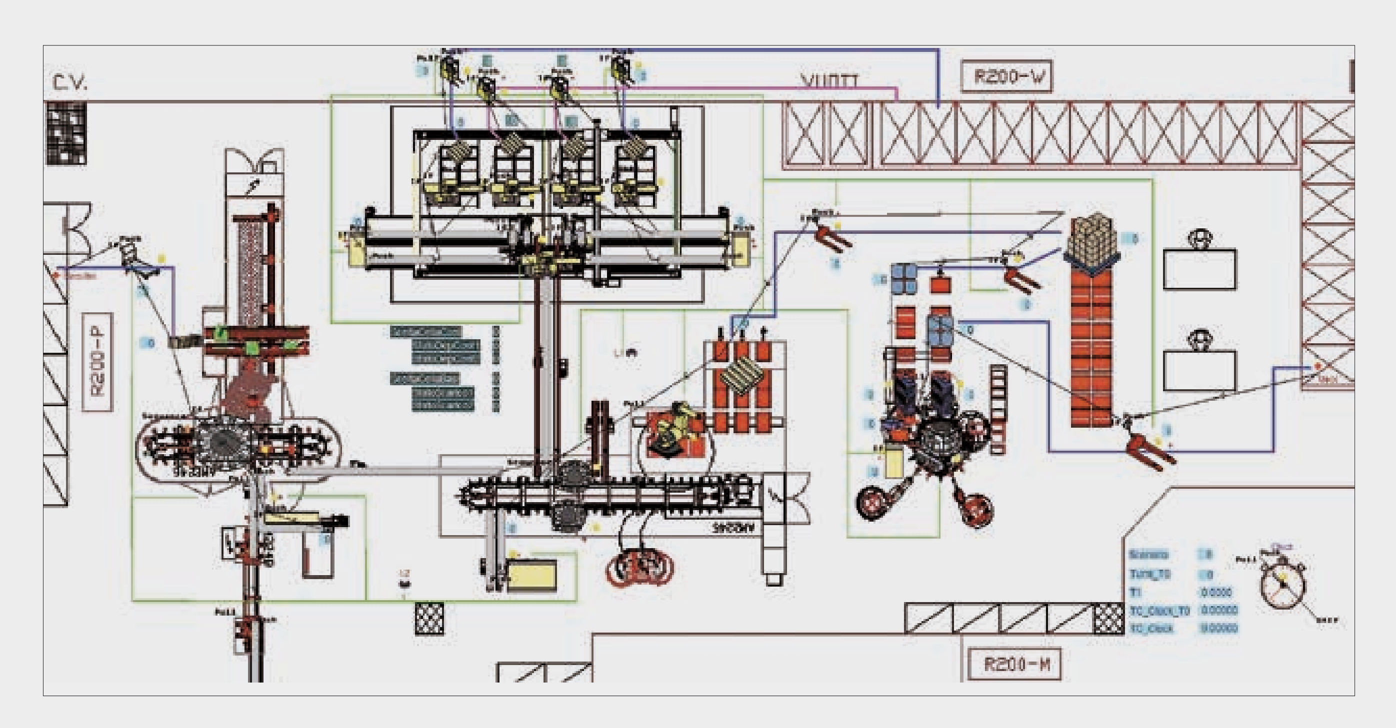
This method, along with other, adaptive, production-mix-based, heuristic approaches and empirical recipes deduced from field best practices, is now a component of the short-term (one-week) line scheduler in use at the ABB vacuum circuit breaker plant in Dalmine, Italy. The blending of different tools into a flexible and reactive system, easily interacting with human intelligence, is itself a heuristic super-tool, in response to complexity and chaos.

Exact analytic modeling

Problem simplification is always a good first approach. A feeling for variable sensitivity and order-of-magnitude effects also helps problem formulation. This is exactly what is required, for example, when simulating sales figures – a saturating revenue curve, modeling both

Often, computing an exact solution takes too long so, in many cases, a suboptimal solution may be a more reasonable option.

3 Discrete event simulation of the "end-machine" portion of F200 residual current device assembly line in ABB's Santa Palomba plant in Italy



Problem simplification is always a good starting approach. A feeling for variable sensitivity and order-of-magnitude effects also helps problem formulation.

the virgin and the mature market regimes, may be described by a differential equation with some parameters that can be derived from available historical market data. Coupled with a revenue-dependent cost curve, a differentiable analytical model can be generated that is simple enough to solve in closed form – allowing earnings and their maximal values to be identified ➔ 2.

Stochastic systems

Many processes have uncertainty in their input data, so these are often expressed as a probability density function (PDF) that describes, for each input, the probability of each of their admissible values occurring. Naturally, the process output data is then nondeterministic. Various methods are available to describe this unpredictability.

The celebrated Monte Carlo (MC) method constructs the output PDF by running many (often over a million) randomly chosen inputs through a black box deterministic simulator. The asymptotic convergence rate is independent of the number of input data items (this does not mean that with few or many random variables the convergence time is the same). MC is simple to understand and cheap to implement, but is often too slow.

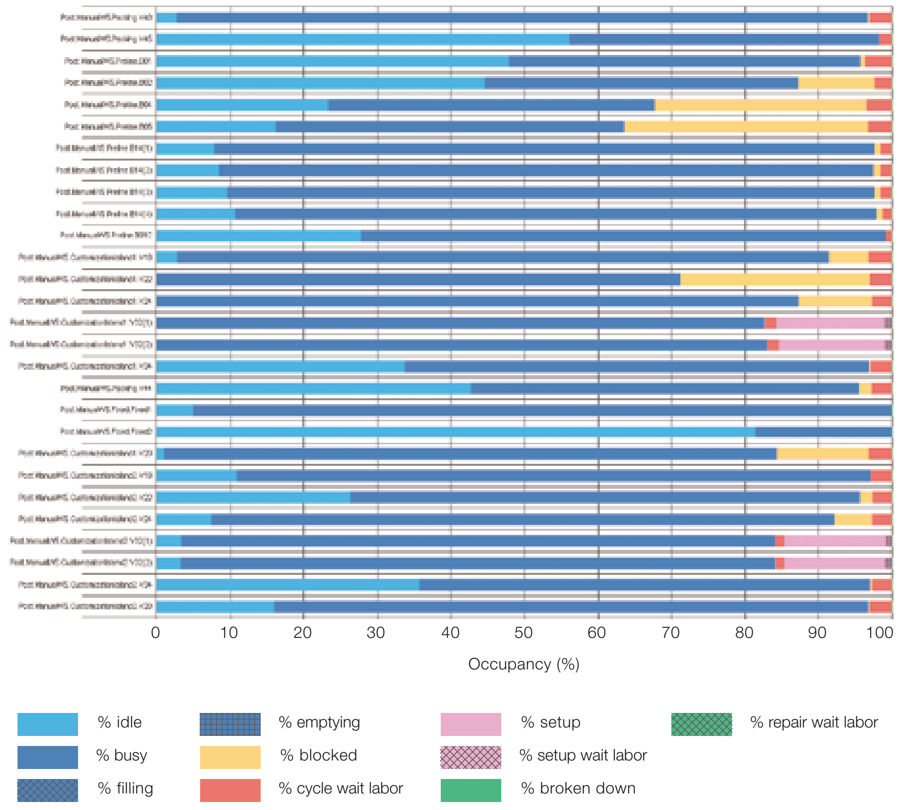
A recent alternative is the so-called polynomial chaos (PC) method. The basic idea is to expand the output PDF into a truncated series of known basic functions; for instance, orthogonal polynomials (hence the name). Polynomial orthogonality allows rapid determination of the expansion coefficients, typically with only very few runs of the deterministic simulator.

Discrete event simulation

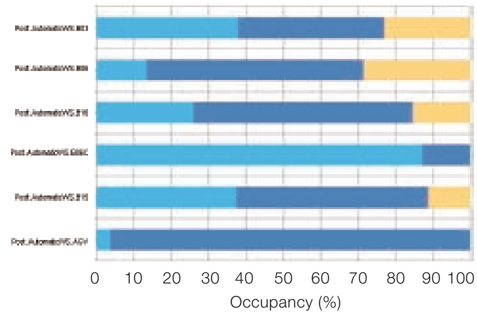
High-level, strategic, quantitative methods, such as MP, help, but are not sufficient, to accurately mirror real-life situations. Late part delivery, machine breakdown and maintenance, manpower scheduling and the other complicating factors that dog typical production operations also have to be taken into account.

A solution is discrete event simulation. This involves a virtual replica of the factory (or logistic network, warehouse, etc.) that reflects items passing through the different production stations and the effects on the process of deterministic and stochastic interference. Commercial tools can be used to reproduce the real system to the required level of detail and to run different scenarios to determine the optimal manpower distribution, machine allocation, scheduling strategy and so on.

4 Occupancy after a discrete event simulation. Color codes indicate busy, blocked upstream or downstream, waiting for labor or repair, etc.



4a Machine occupancy



4b Manpower occupancy

Several ABB factories have been analyzed with discrete event simulations. These yield visual and intuitive representations, like CAD views of the layout that are animated with workers, parts and products moving from machine to machine → 3. One of the main results is a set of tables showing the actual amount of time spent processing by workers and machines, or idle time caused by, eg, upstream or downstream bottlenecks or repair demands → 4. This information is fundamental to appropriate resource allocation.

A continuous effort

In some cases, a one-off simulation suffices. In others, the simulation may become an integrated tool, to be used on an ongoing basis. Either way, if a constant, empirical validation is absent then effective modeling and simulation is hardly possible.

The key prerequisites for a successful implementation of the techniques discussed here are a firm commitment together with a well-structured approach to data collection and management. The latter implies an investment that goes beyond the implementation of a given IT solution and whose return is tangible also in absence of simulations.

Simulations quantitatively evaluate cost-saving or empowerment actions before they are taken and enable better-run operations both in the short-, medium- and long-term. So, a thorough and skillful application of MP techniques can make significant improvements to a company's bottom line.

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Simulation Toolbox

Dielectric and thermal design of power devices

ANDREAS BLASZCZYK, JÖRG OSTROWSKI, BOGUSLAW SAMUL, DANIEL SZARY – Demands and trends in power devices are toward compactness and cost efficiency, so developers are forced to employ solid/gas hybrid insulation and optimize the shape of electrodes to keep the withstand voltage above acceptable levels. In addition, high device current ratings can cause heat dissipation problems that would require a complex cooling system, thus increasing device size and cost, so clever thermal design is also essential. Simulation software helps the designer accommodate these dielectric and thermal aspects but they typically involve specific analyses not offered by standard engineering simulation tools, especially when evaluating electric discharges and coupling between the fluid flow and electromagnetic effects. This gap has been narrowed by the Simulation Toolbox, a proprietary collection of simulation tools and procedures created by ABB.

The fundamental advantage of the network approach is the performance.

The creation of the ABB Simulation Toolbox in the 1990s was strongly driven by a need to let designers simulate complex dielectric and thermal situations in power devices without involving dedicated simulation experts. At the same time, the Simulation Toolbox has been made easy to use:

– The simulation procedures are directly integrated into the design tools, eg, computer aided design (CAD) or product-specific design systems. The major part of the user interactions can be performed within the native design system without involving specialized third-party tools.
– The learning time for specific simulation procedures is a few days or weeks.
– The simulation procedures deliver the answers for typical problem formulations within a reasonable time, when possible.
– The simulation procedures are constantly improved and updated by ABB researchers and their university partners.
– The hardware and software infrastructure required for high-performance simulations is available via the ABB intranet. No investments are required at the developer sites.

The platform is now accessed by more than 100 users worldwide who submit more than 10,000 simulation jobs per year.

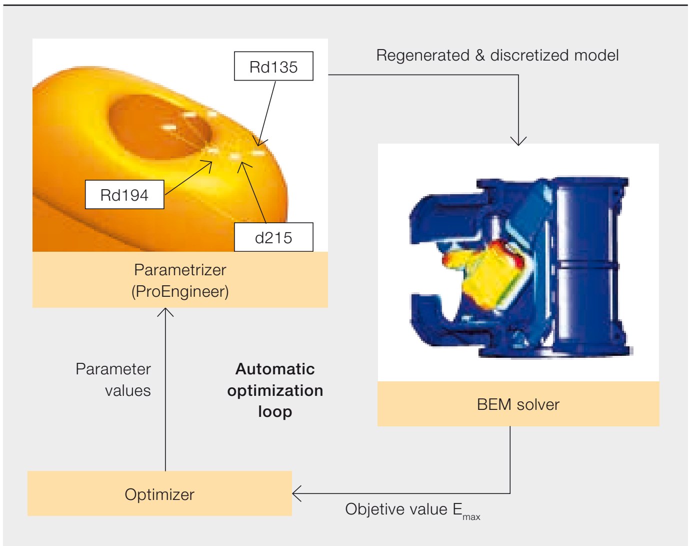
The first implementation of the Simulation Toolbox, based on a Beowulf Linux cluster created during a university project more than 10 years ago [1], was well received at ABB. The platform is now accessed by more than 100 users worldwide who submit more than 10,000 simulation jobs per year. It is maintained by a dedicated team that provides support and training.

Title picture
Simulating the thermal and electromagnetic behavior of compact power devices requires more simulation horsepower than any commercially available product can supply. The ABB Simulation Toolbox provides the extra muscle needed.

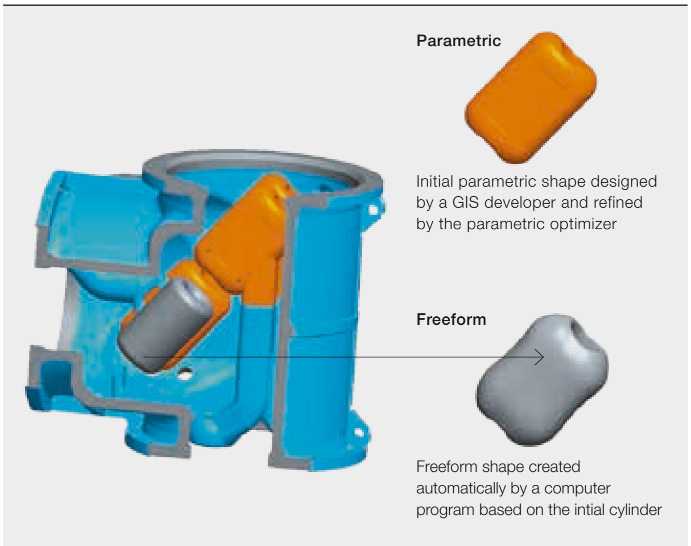
Boundary element method

Typically, the first step of a dielectric simulation involves calculation of the electrostatic field for a complex 3-D geometry. This type of computation, based on solving the linear Laplace equation, has been available in many commercial electromagnetic software packages since the 1980s. However, truly effective simulation re-

1 Parametric optimization for dielectric design of gas-insulated switchgear: the basic procedure architecture and an example computation



2 Freeform dielectric optimization of a GIS component



Recently, in a cooperation between ABB and several European universities, another optimization approach has been investigated: freeform optimization.

quires the ability to model down to very small detail in 3-D since it is this detail that usually determines overall design quality. In the early 1990s, ABB demonstrated that the so-called boundary element method (BEM) was efficient at solving very complex and detailed models. This technique formed one of first components of the Simulation Toolbox and is still widely used by ABB engineers today [2].

Parametric optimization

The fundamental advantage of the Simulation Toolbox approach is its inherent close integration with CAD systems, covering boundary condition definition, material properties and meshing. In contrast to finite element tools, the meshing of the outer space (the so-called airbox) is not required. All these features enabled fully automatic creation of discretized (meshed) models and opened a new area of advanced dielectric design: parametric optimization → 1. The procedure – developed together with a university partner [3] – performs, for every calculated case, many hundreds of complex 3-D computations fully automatically. Typically, a designer submitting a prepared CAD/ProEngineer model to the Simulation Toolbox system receives, within a few hours, a response either in the form of an optimized geometry or a sequence of results for a prescribed set of geometrical parameters.

Freeform optimization

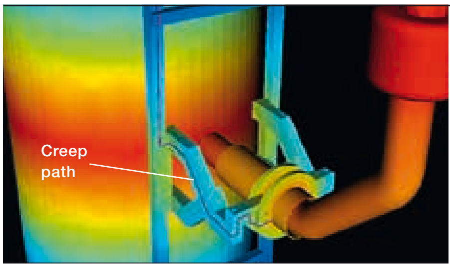
Recently, in a cooperation between ABB and several European universities, another optimization approach has been investigated: freeform optimization [3]. This numerical procedure is based on a formulation of the “adjoint problem,” which delivers the gradient information used by the optimizer for changing the mesh nodes coordinates. In contrast to the parametric approach, freeform optimization does not require specification of geometrical parameters. Instead, the computer algorithm creates a new shape and this significantly reduces the effort designers have in preparing the initial geometry. In the example shown in → 2, a simple cylinder has been applied as the initial geometry. The freeform optimizer has converted the cylinder to a new shape that is very similar to the result of the parametric procedure. The new method still requires some research but, as a component of the Simulation Toolbox, it can be made available for ABB engineers immediately – long before a similar procedure can be offered by commercial tools.

Dielectric design for transformers and switchgear

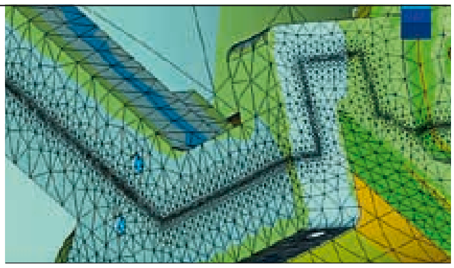
Predicting the withstand voltage is one of the trickiest simulation tasks in power device design. A knowledge of the maximum field strength is not sufficient to make predictions about insulation effectiveness in complex physical arrangements involving insulating barriers and electrodes embedded in solid dielectrics.

It is essential to properly evaluate the characteristics of a discharge (streamer or leader) that may be initiated at critical spots. A properly designed insulation

3 Example of discharge path evaluation: creep path defined for a power transformer along an output lead support

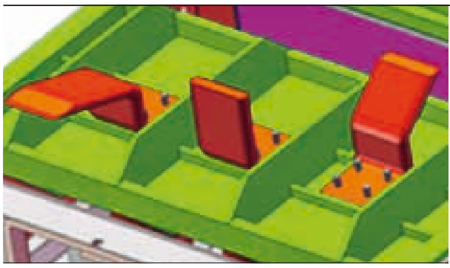


3a The potential distribution

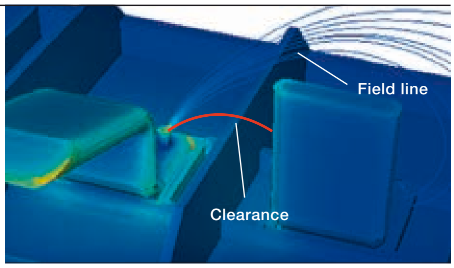


3b The field strength distribution

4 Example of discharge path evaluation: medium-voltage air-insulated switchgear with hybrid insulation.



4a Overall view of terminals



4b Field lines for evaluation of inception voltage and the streamer path over the clearance between the inception point and the neighboring phase (red path)

Truly effective simulation requires the ability to model down to very small detail in 3-D since it is this detail that usually determines overall design quality.

system should ensure that, even if a streamer inception occurs, the propagating discharge will be extinguished on the way between the electrodes and the probability of breakdown will be small enough to pass the dielectric type tests.

The potential distribution for a creep path along a transformer output lead support can be simulated and the designer can check whether the cumulative creep stress is within the range permitted by the ABB technical standard → 3. Similarly, the field lines for a terminal in a medium-voltage switchgear component can be computed and used to evaluate the streamer inception voltage for which the number of electrons generated by the avalanche mechanism is sufficient to create a self-propagating streamer head → 4, If the inception should occur, further dimensioning must be based on the clearance between the inception point and the neighboring electrode; the designer will check that the average field strength along the clearance is lower than the empirically determined streamer stability field for the positive impulse in air [4].

Electrothermal simulations

Simulation of temperature rise in power devices is a complex task. Conductors are heated by power losses from resistive and inductive currents, cooled by convection and heat radiation, and heat is distributed by conduction. Thus, interaction of electromagnetic, fluid dynamic and radiation phenomena must be considered in the simulation – and these are difficult enough to simulate individually.

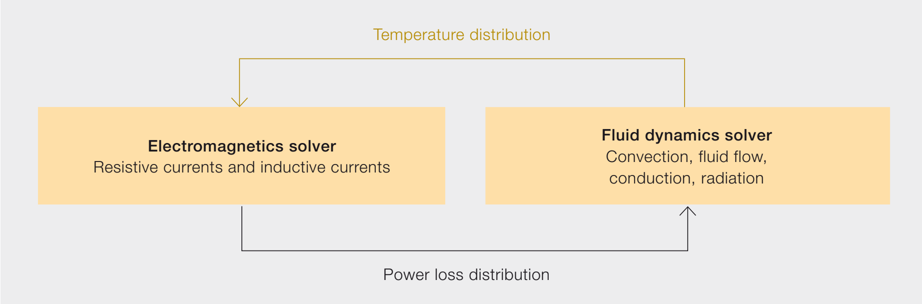
In electromagnetics, resistive currents are dominant, but sometimes inductive phenomena like the skin effect and the proximity effect have to be taken into consideration. Turbulent convective cooling is still a challenge in computational fluid dynamics (CFD), especially for natural convection. That is why a hierarchy of computational methods has been developed for electrothermal simulations.

Coupled electromagnetic and fluid dynamic computations

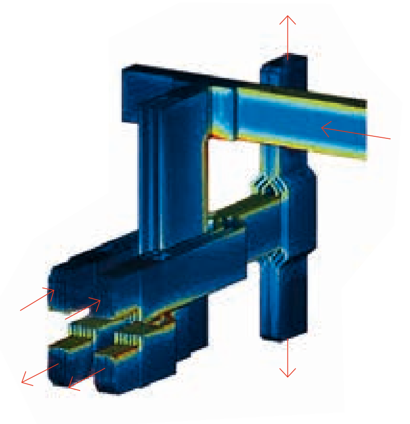
A numerically rigorous treatment of the electrothermal simulation problem is based on the so-called weak two-way coupling of an electromagnetic field solver with a CFD solver → 5. All the above-mentioned physical effects can be taken into account by using the well-established finite element method for the electromagnetic field simulation [5] and the finite volume method for the fluid dynamics simulation (as in the commercial

The ABB Simulation Toolbox lets designers simulate complex dielectric and thermal situations in power devices without involving dedicated simulation experts.

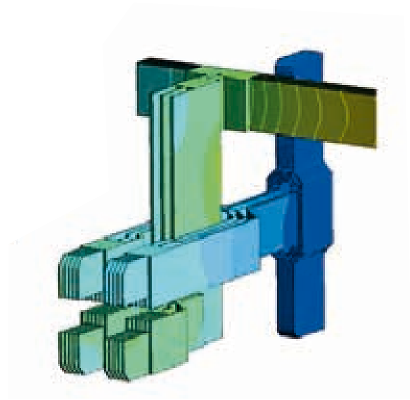
5 Electrothermal coupling: The power loss distribution is computed by the electromagnetic solver and is mapped to the CFD solver, which returns the temperature distribution.



6 A coupled electromagnetic/thermal computation for a low-voltage busbar system



6a Current distribution (calculated by the electromagnetic in-house solver [5]). Current in/outflow is depicted by red arrows



6b Temperature distribution (calculated by Ansys/Fluent)

Ansys/Fluent formulation, for example). A two-way coupling is necessary if the temperature dependency of the electromagnetic material parameters is to be considered. If the temperature dependency is negligible, or if the approximate temperature is known in advance, then material parameters can be anticipated and a one-way mapping of the power loss distribution is sufficient.

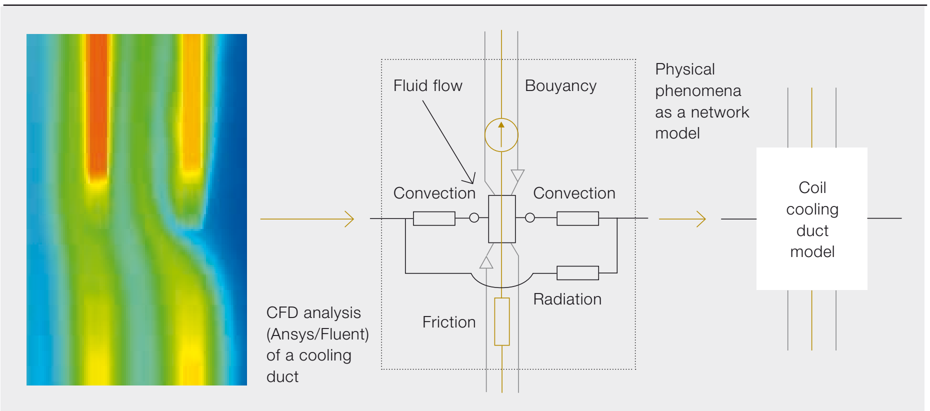
This computational method is favorable if inductive effects play an important role or if there are local hot spots in the temperature distribution. Then, loss distributions and temperature distributions must be spatially well resolved. An example is given by the high current busbar system (a low-voltage switchgear part) → 6. The power loss distribution is strongly influenced by the skin effect and the proximity effect in the busbars → 6a.

However, this rigorous and locally precise electrothermal coupling is a complex procedure that consumes many man hours because the geometry has to be meshed and computed with two different coupled solvers. Therefore, it is desirable to come up with a simpler computational method for less demanding design cases.

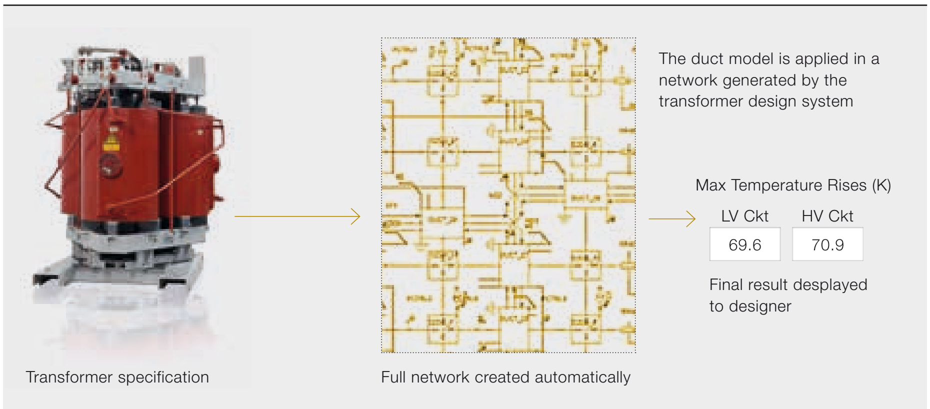
Thermal and pressure networks

The network approach offers an attractive alternative to the complexity of coupled electrothermal analysis [6]. The basic idea is to substitute geometrical components with abstract network models that include thermodynamic and electromagnetic formulations valid for a specific part of the device. An example of such a model representing a cooling duct of a transformer coil is shown → 7. Its internal topology includes a very few network elements that are responsible for modeling the physical phenomena inside of the duct: heat transfer through the boundary layers (convection), fluid flow, friction factors, buoyancy head and radiation. The elementary models are validated using advanced CFD methods and are encapsulated into ready-to-use network components. These can be used by developers of transformer design systems for creation of the full transformer model in order to calculate the winding temper-

7 Network approach applied to thermal simulations of transformers



7a Development of encapsulated network models validated by CFD simulations



7b Application of encapsulated network models in a transformer design system to calculate the winding temperature rises

ature rises [7]. The accuracy of such network computations is acceptable – a few Kelvin. The error is largely determined by uncertainties in input data and manufacturing/measurements tolerances rather than by network model simplifications. The fundamental advantage of the network approach is the performance: The fast computation times, in the range of milliseconds up to a few seconds, enable integration into interactive design systems and the use of optimization algorithms that require many hundreds or thousands of computations to design a transformer.

Outlook

The dielectric and thermal simulations integrated into the ABB Simulation Toolbox platform have now become well established in power device design. The platform provides a bridge between the product developers and ABB researchers and their university partners. This ensures that the newest achievements in simulation technology are continuously applied in the design of ABB power products.

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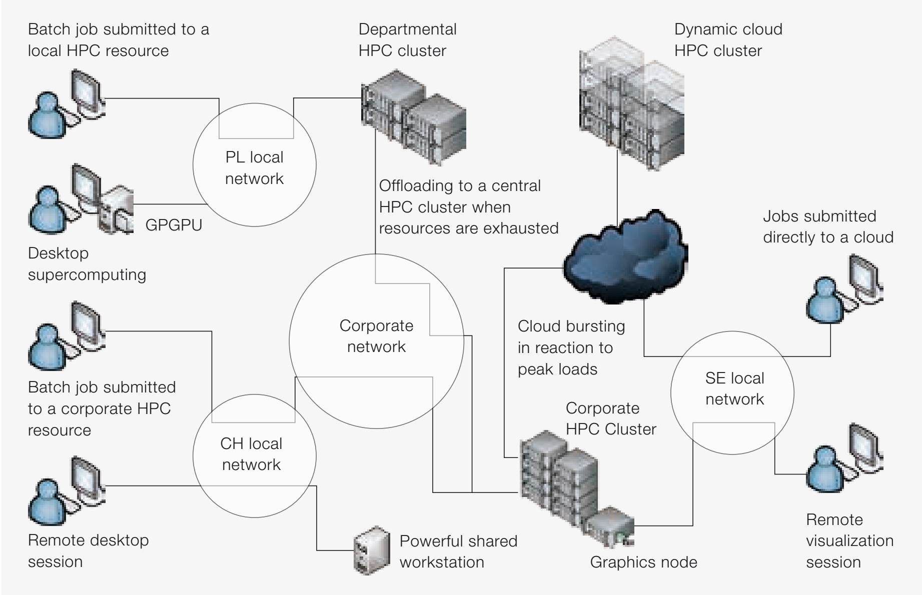
Resisting obsolescence

The changing face of engineering simulation

BARTOSZ DOBRZELECKI, OLIVER FRITZ, PETER LOFGREN, JOERG OSTROWSKI, OLA WIDLUND – One of the many benefits of computer simulation is the ability to solve complex industrial problems quickly and relatively cheaply. Computer simulation is an evolving field, and the interplay between research in numerical methods and developments in computer architecture is ensuring progress. Recent changes in the landscape of information-processing technology have been characterized by increasing parallelism in this regard. Many simulation tools are now able to utilize tens of computing cores to solve bigger and more complex problems with increased accuracy in practical timescales. In addition to commercial simulation packages and customized ABB proprietary tools that are developed in-house, there is also a growing number of tools developed by open-source communities. What are the forces influencing such changes in simulation in engineering applications?

1 Future landscape of computational infrastructure for simulations



Infrastructure diagram mixing the current state with possible future directions

Simulation is an important element of product development at ABB – compared with physical prototyping, it is often faster, less expensive, more detailed and better able to provide innovative ways of solving complex industrial problems. So how is this achieved?

Clusters, clouds and desktop supercomputing

The key to simulation is, quite simply, high-performance computing (HPC). With this in mind, ABB has invested in its own computational clusters over the years. Today the company has a number of dedicated HPC resources available internally. While large HPC systems allow simulation of the most complex products, they are not the only computational resources used by simulation experts.

Commoditization of high-end computing, together with the multicore revolution, brought parallel scalability to the desktop. Many simulations are being performed locally on fat workstations (ie, one computer does all the computation). For a while it seemed that a desktop simulation approach – ie, bringing supercomputing to the desktop – would become prevalent with the emergence of GPU (graphics processing unit) accelerators dedicated to number crunching, but this disruptive technology has yet to deliver on the front of engineering simulations.

Another emerging force with the potential to reshape the simulation infrastructure is the rapid development of publicly available data centers, which provide computational power on demand using a pay-per-use charging model. This new model of outsourcing infrastructure is widely known as cloud computing.

General-purpose clouds are poorly suited for simulation workloads, which often require specialized networking solutions characterized by high bandwidth and low latency. However, some cloud providers design parts of their data centers with HPC requirements in mind. Initial cloud benchmarking experiments performed by ABB indicate that distributed-memory parallel applications with a moderate amount of message exchanges achieve satisfactory performance. Simulated cost projections based on historical usage data extracted from ABB's current HPC system suggest that moving suitable workloads to the cloud could halve the total cost of ownership for supporting infrastructure. The biggest hurdle with respect to corporate use of cloud computing is information security. Much work needs to be done in this area before engineering companies and their clients will be willing to store and process their data on an infrastructure that is outside corporate control.

In the short term, a centralized HPC resource will likely be the most cost-effective solution. Such a resource may be augmented by smaller, localized departmental clusters. The potential landscape of the future computational infrastructure for simulations is presented in → 1. In the future, in addition to GPGPU (general-purpose GPU) powered workstations, there may be a more dynamic setup where peaks of activity are dealt with by transferring some of the load among corporate resources and using cloud bursting (ie, utilizing a public cloud) in cases where internal resources are exhausted.

The key to simulation is, quite simply, high-performance computing (HPC). With this in mind, ABB has invested in its own computational clusters over the years.

Title picture
As information-processing capabilities evolve, so too do the simulation tools used to engineer new products.

An emerging force with the potential to reshape the simulation infrastructure is the rapid development of publicly available data centers.

With the infrastructure in place, suitable processes need to be developed to ensure efficient use of available hardware and software resources.

Ensuring efficient resource utilization

The cost of investing in and maintaining HPC hardware is usually lower than the cost of licensing the simulation software. In order to dimension and use these limited resources efficiently, a balance must be reached among several factors: the number of available CPU cores, the hardware topology (shared or distributed memory), the cluster interconnect (communication speed), the number of available licenses and the configuration of queue systems (eg, to maximize throughput of batch simulations, but still have licenses available for daytime interactive use).

The weighting of these factors is influenced by the licensing model used by the software vendor. Usually one costly single-core license is consumed for each job, while each additional CPU (central processing unit) core consumes a cheaper HPC license. Most vendors have a degressive pricing for the HPC licenses, so that the cost per HPC license decreases with the number of licenses acquired. The pricing is usually such that it is desirable to run each simulation on as many cores as possible, for as short a time as possible, so that the costly single-core licenses are used as efficiently as possible.

Over the past eight years, an extensive collaboration has evolved within ABB for coordinating and sharing both hardware and software resources. This effort started rather informally with some of the larger simulation teams, but is now supported by the global IS/IT organization. The main objective is to be cost conscious, but sharing resources is also advantageous in other ways. For teams with low-volume usage, or for new users, it is possible to share the resources of other teams for a limited amount of time. This simplifies testing and evaluation of simulation tools and limits the initial investment. Especially for the corporate research centers, the ability to easily share hardware and licenses with business unit partners is very important for technology transfer within projects; users in the business units can easily get early access to the tools and models developed. Most software vendors have also recognized the benefits to them; eg, giving new users easy access to their products and gaining a better overview of customer needs.

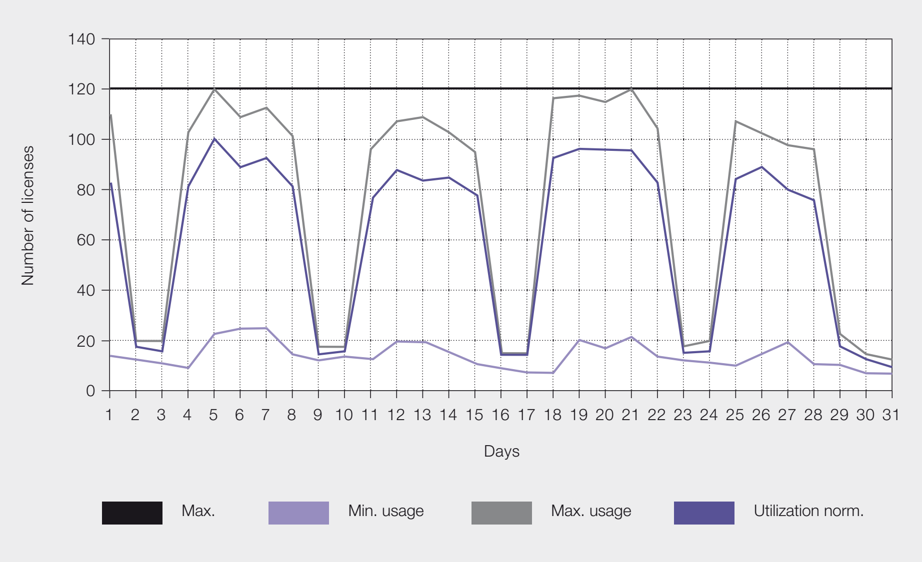
The ability to share software licenses across units and geographical locations usually involves special global-level contractual agreements with the software vendors. The advantage then is that ABB becomes a more visible customer. Today ABB has global contracts and license pools in place for several large simulation-software suites.

A good example of sharing of HPC hardware resources is the new Linux cluster ”leo” hosted by one of ABB’s corporate research centers. This cluster is used mainly for complex fluid mechanics simulations and molecular dynamics simulations. Leo is jointly financed by two corporate research centers, and is used by several teams in multiple countries. Another cluster, ”krak,” is financed and maintained by a third corporate research center, but for practical reasons is co-located with the leo cluster. Krak serves as a computational backend for the ABB Simulation Toolbox, a distributed system that provides the company’s worldwide business unit partners with transparent access to HPC resources.

Sharing of resources of course has its challenges. Some are of a technical nature and are usually easy to resolve, but there are many more difficult “soft” issues that must be addressed, eg:

- How to resolve conflicts
- How to accommodate for different usage patterns
- Determining who should pay for new resources when there is a shortage
- How to interpret license statistics

2 ABB's eLicense tool



The tool allows for optimal license utilization by giving invaluable input to the license purchase processes.

Over the past eight years, an extensive collaboration has evolved within ABB for coordinating and sharing both hardware and software resources.

As for sharing of software licenses, the key to success is to implement a well-defined process for the governance of the license pool; that is, to define common policies and rules for resource usage, anticipate potential problems and propose solutions. This could entail telephone conferences with representatives from all teams contributing to the pool, but there could also be a smaller group of people handling day-to-day issues. To ensure fairness and smooth conflict resolution, when needed, it is extremely important to collect and monitor usage statistics, and to make the information available to all users. For this purpose, ABB has developed a Web-based tool called eLicense for managing license pools and monitoring license usage ➔ 2.

Physical models and numerical methods

A starting point for any simulation tool is a mathematical model that describes the physical phenomena of the process. Once it is developed, a numerical algorithm that carries out the calculation of the model can be implemented.

Mathematical models and numerical algorithms are as important as the computer itself. For example, it would be impossible to compute the electromagnetic field in a transformer by choosing an atomistic model even on the fastest supercomputer. Instead, a model is created by averaging the behavior of atoms and electrons and deriving bulk material properties. This bulk description combined with the fundamental electromagnetic field equations (Maxwell's equations) results in a model that is suitable for the simulation of the electromagnetic fields in a transformer.

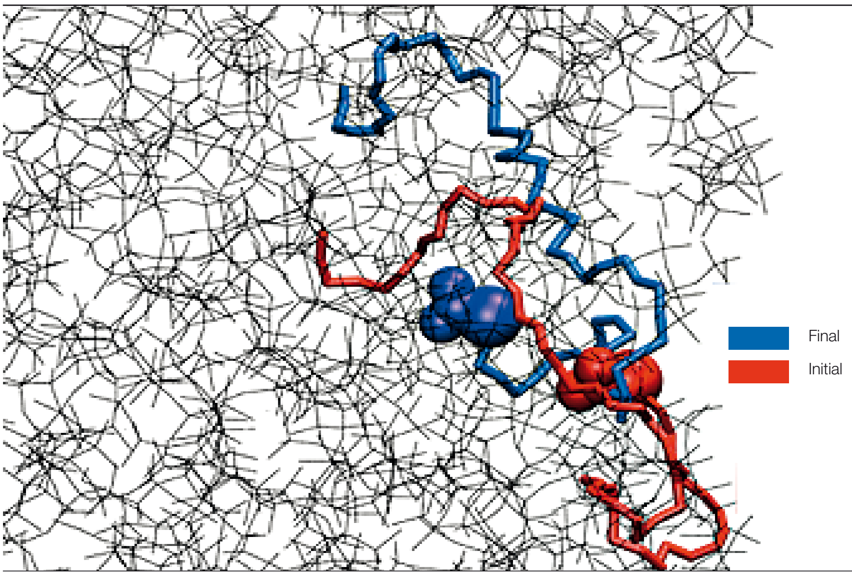
Still, this is not enough. After choosing a suitable model on an adequate level of simplification, the computer must be told how to calculate the model. This means an algorithm for solving the constitutive mathematical equations of the physical model on the computer must be chosen and implemented. This is called a numerical method. The finite element method is an example. The numerical method has to be chosen such that the computation is precise, fast and robust. A good computational method is a problem-dependent, well-coordinated combination of physical model, numerical method and hardware.

Classical simulation tasks in engineering include structural mechanics problems, fluid dynamics problems and electromagnetic field calculations. Good computational methods for these standard tasks are often available as commercial or open-source software products. Nonstandard simulation, however, requires the development of customized computational methods on all three levels – modeling, algorithms and hardware.

Complications can result from nonstandard material properties or from special geometrical settings. Nonstandard types of simulations include multiphysics computations, in which several physical domains have to be

ABB engineers employ the most efficient tools and the most powerful models to give its customers the best possible products.

3 Molecular dynamics simulation



An initial and final orientation of a charged molecule near the surface of a PDMS insulator are shown. In the final configuration, the charged group is buried more deeply in the bulk.

coupled. The growing interest in these calculations forced commercial vendors to introduce this coupling into their products. However, for some combinations of physical phenomena there are no off-the-shelf solutions available or the existing ones are inefficient. An example of phenomena important in ABB products that are poorly supported by existing tools are arc processes, where fluid dynamics and electromagnetism have to be coupled.

Beyond the classical domains tractable with mesh-based methods, such as finite elements, are elaborate computational methods for molecular or even atomistic processes. The best known ones are the density functional theory (DFT) and molecular dynamics (MD). Although these highly advanced computational methods are not expected to become as important for ABB as they already are in the pharmaceutical industry, there is increasing ambition to apply these methods to resolve important material science questions. In the field of insulation for high-voltage AC and DC transmission systems, eg, they improve the microscopic picture of electric transport and other dynamic processes. A concrete application of the molecular dynamics method was recently developed in collaboration with IBM Research. Diffusion of light-weight molecules in silicone-rubber polymers (PDMS) was calculated to explain an important surface-hydrophobicity restoration process crucial for the long-term stability of HV outdoor cable insulation. As shown in ➔ 3, a net orientation and polarization of molecules with methyl groups on the surface could be simulated. This result offers an explanation for the loss of surface hydrophobicity in the case of oxidation. It also explains the restoration of hydrophobicity through a particular interaction between cyclomethicone molecules, oxidized methyl groups, and Na+ ions.

ABB's path in a changing landscape

The breakthrough of cloud computing and GPU technology with respect to numerical simulation technology may be a long time coming, but parallel simulations on multi-core computers and clusters are already essential.

By sharing hardware and software resources, different teams within a company can obtain easy and cost-efficient access to the latest simulation technology and hardware resources. At ABB this means R&D results and best practices can be efficiently transferred between its research centers and business units.

Market research reports invariably show that the most successful industrial companies are those that make use of modern numerical simulation tools in their product development. ABB engineers employ the most efficient tools and the most powerful models to give its customers the best possible products. When it comes to advanced customized simulation tools, the wheel will not be reinvented when there are already good tools available, but ABB's scientists will never hesitate to break new ground in areas where ABB has technology leadership.

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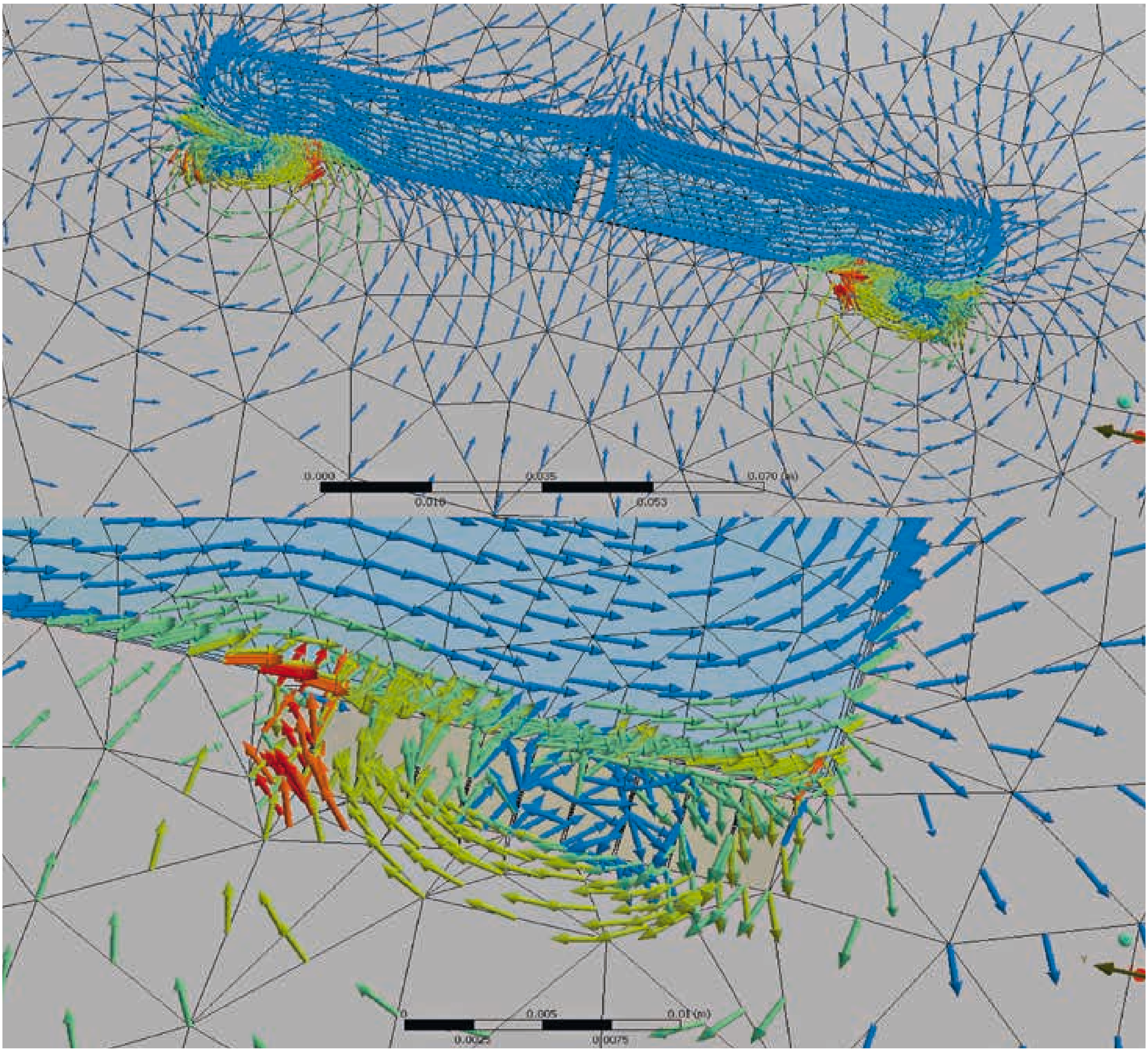
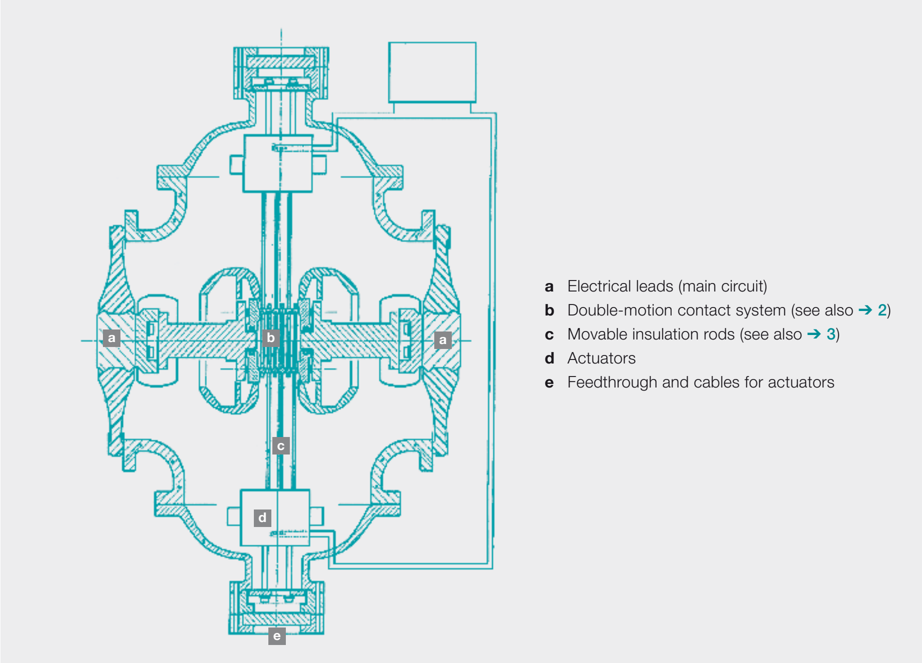


Opening move

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)



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-

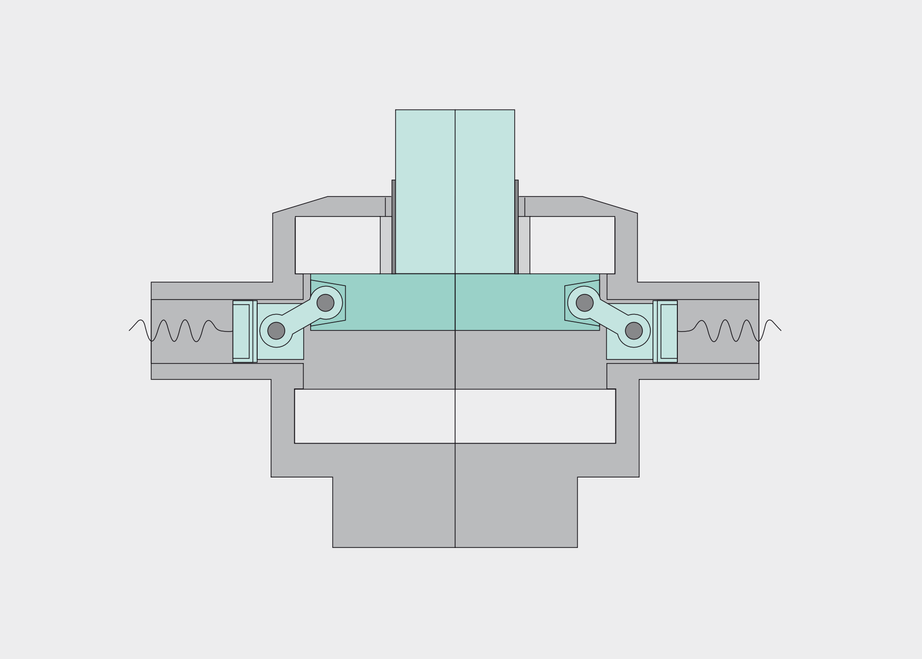
Title picture
Flux density distribution in intersection of coil and plunger in finite element simulation.

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

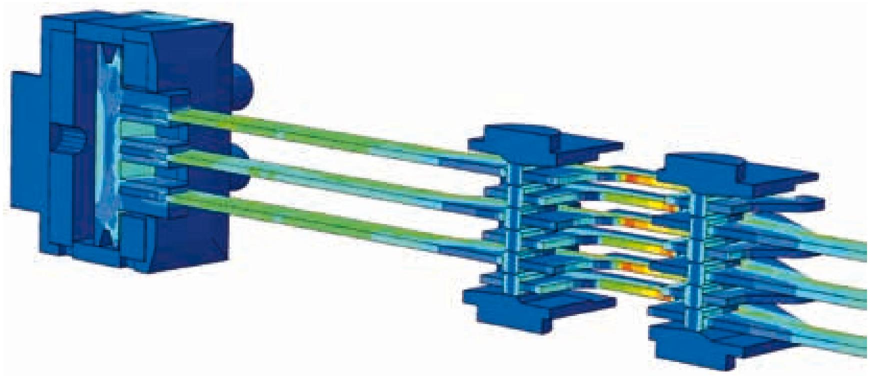
Different simulation approaches can roughly be split into two main fields, finite element (FE) models and lumped models. The FE approach (where the geometry can be captured in detail) is the most accurate. Often, lumped models (also called integral models) are good enough to describe the system. They 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 tradeoff 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.

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.

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.

The simulations permit quantities such as strains, contact pressures as well as displacements, velocities and accelerations to be studied, evaluated and visualized ➔ 3.

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

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.

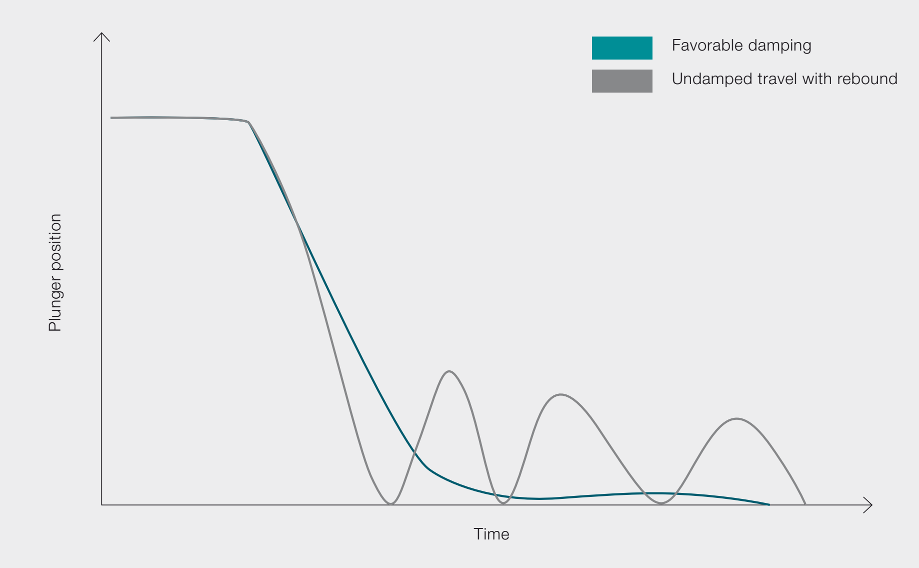
One big challenge for the design was to get good damping for both opening and closing operations without dissipating energy during acceleration.

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.

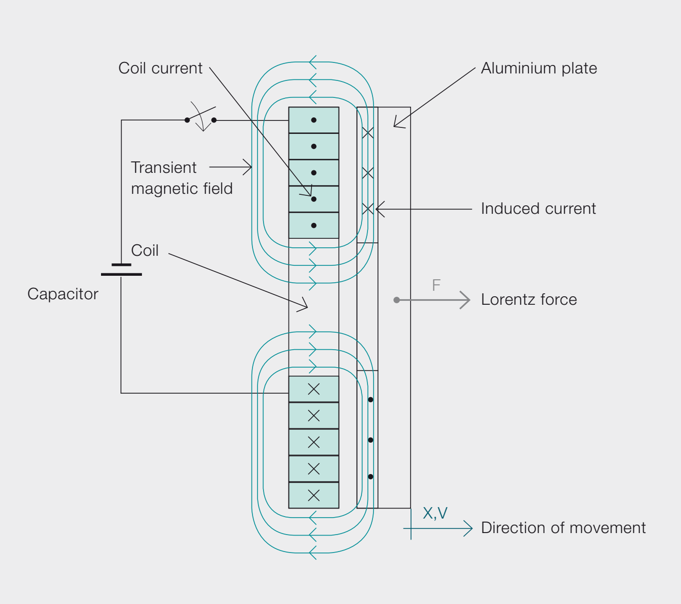
Actuation

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.

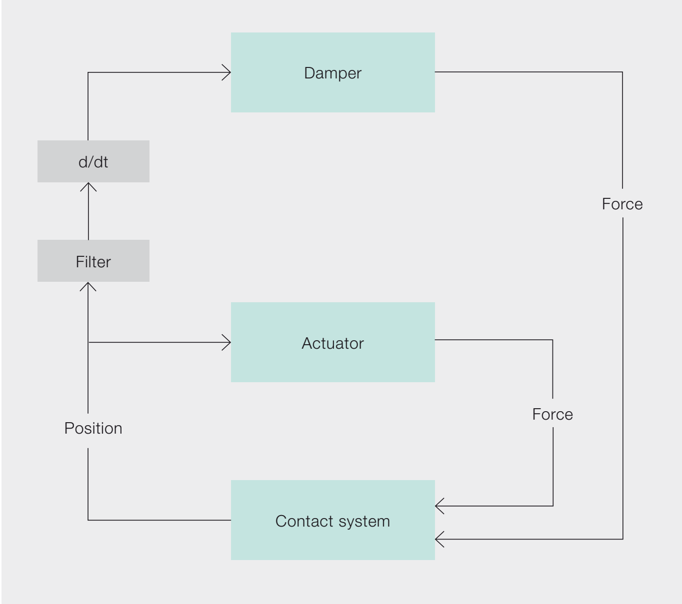
Damping

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

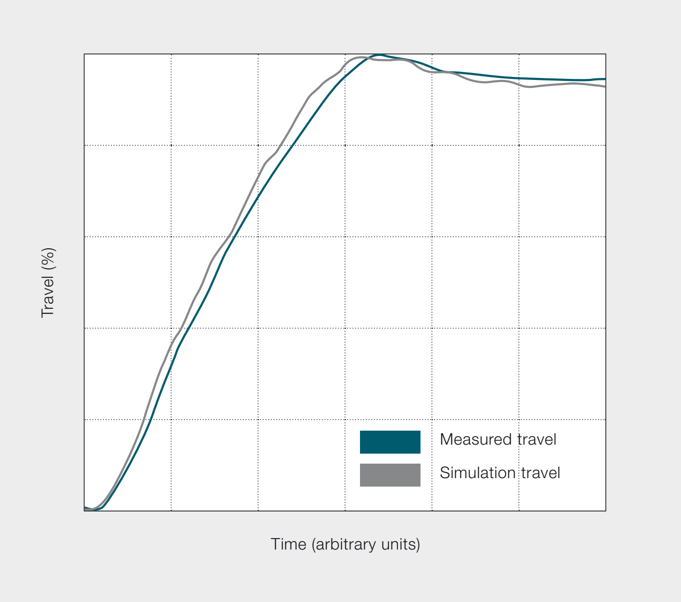
Most of the work performed on the simulations was to reduce the impact of the contacts: The simulation tool was of great help in visualizing the impact behavior.

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.

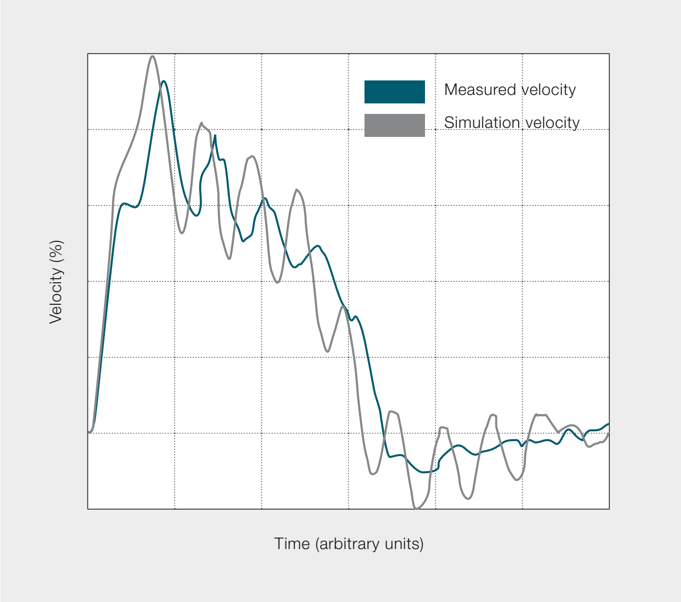
Successful simulation

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:

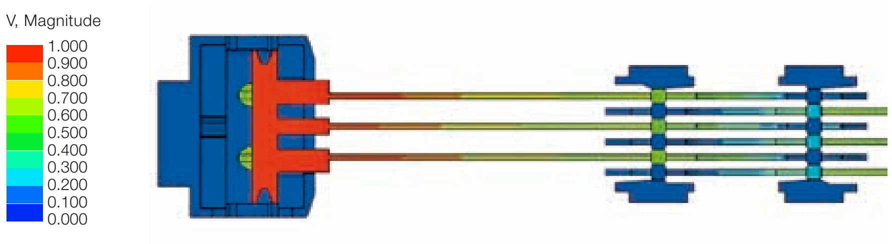


7a Travel



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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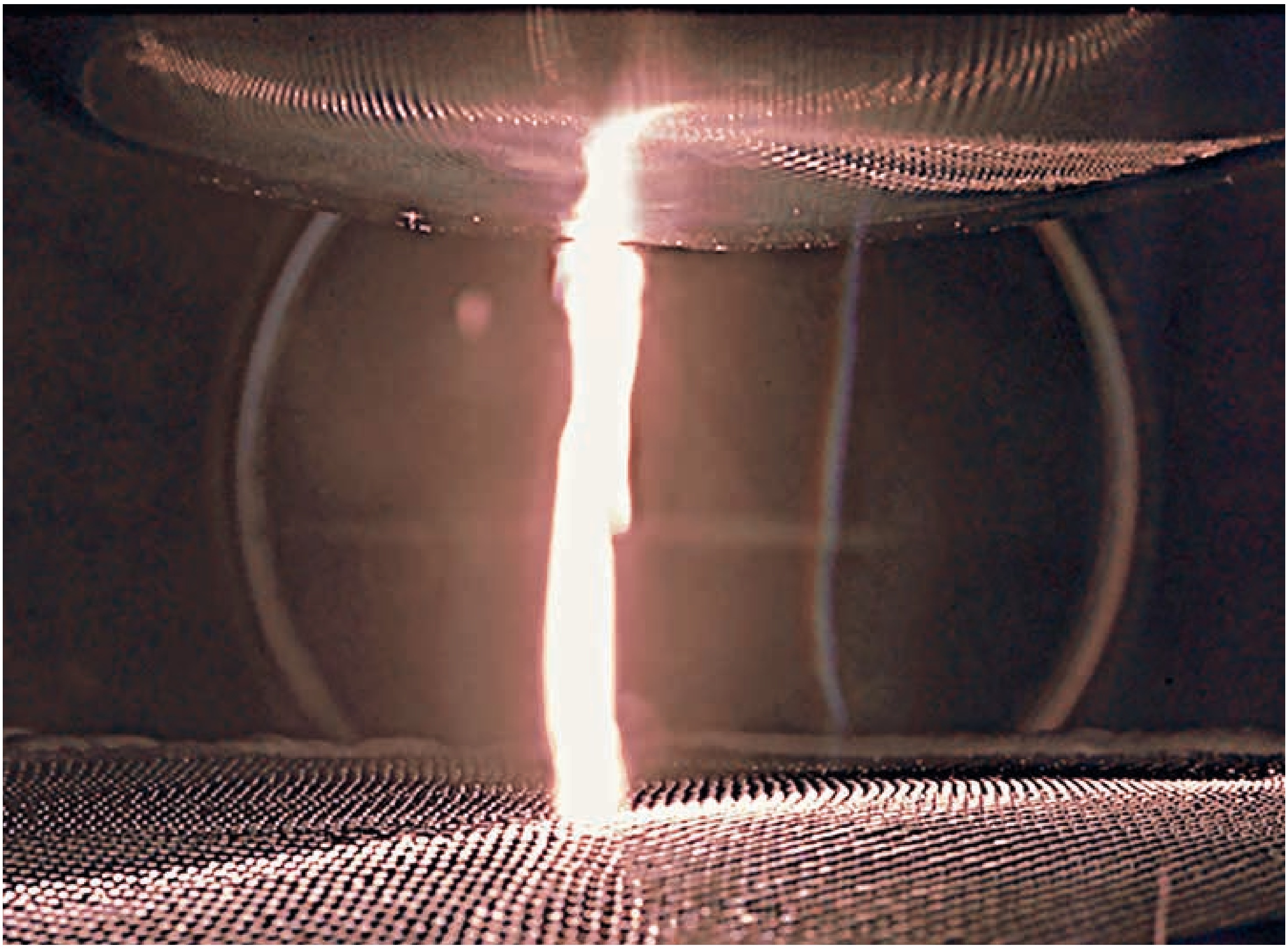
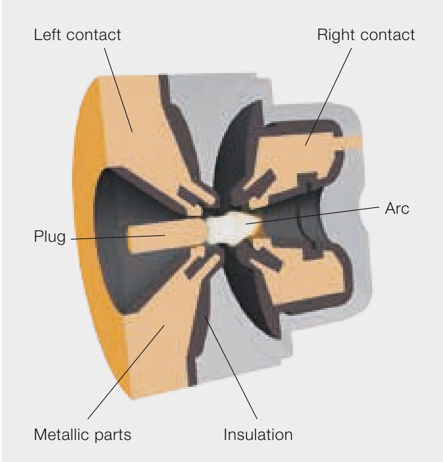


Switching analysis

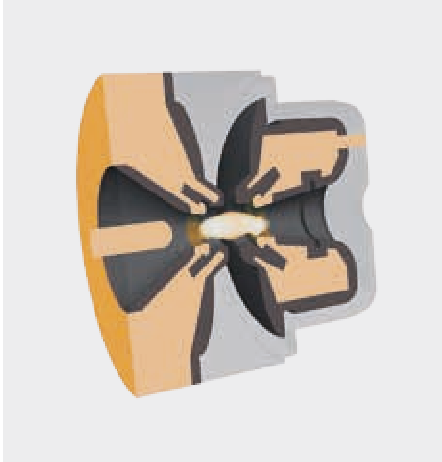
Simulation of electric arcs in circuit breakers

JÖRG OSTROWSKI, MAHESH DHOTRE, BERNARDO GALLETTI, RUDOLF GATI, LUCA GHEZZI, MICHAEL SCHWINNE, XIANGYANG YE – Society is powered by a web of electrical generation, transmission and distribution equipment that reaches almost every corner of every country. Some of the most critical components of this infrastructure are the devices that switch and break the huge currents and voltages that are needed to move the vast amounts of power societies consume. At the heart of these devices lies the chamber where the electrical circuit is actually broken or completed and it is here that electric arcs test the mettle of the designer with some of the most extreme electrical conditions found in any standard equipment. Indeed, one of the most challenging simulation tasks in ABB today is to predict the plasma behavior of these arcs. Recently, tremendous progress has been made in this area and it is now possible to predict many aspects of arc behavior and its impact on circuit breakers.

1 Three-dimensional arc in a HEC 9 generator circuit breaker



1a The plug moves to the left and disconnects the left and the right electric contact.



1b The plug has moved out, the breaker is in the fully open position and the arc burns between the contacts.

The best-known example of an electrical arc is the lightning bolt that lights the sky during thunderstorms. The arcs created between the contacts of a circuit breaker as it opens or closes are on a much smaller scale, but the physical principles are the same: A channel of conductive, high-temperature ionized gas is formed and an electric current flows through it – the arc. The circuit breaker has the task of extinguishing this arc.

The conditions in the arc and its vicinity are extreme. The arc temperature easily exceeds 20,000 °C. In some cases, the pressure in the interruption chamber of the circuit breaker reaches 70 bar. Under these circumstances, measurements can only be carried out to a very limited extent, making product design very difficult and cumbersome. Therefore, simulations of the arc and its physical effects in the interruption chamber are of fundamental importance for the development of circuit breakers.

Title picture

The extreme physical conditions presented by arcing in circuit breakers throw down a challenge to the designer. Recently, there have been significant advances in the understanding and simulation of electrical arcs in breakers. The photo shows an arc imaged by a high-speed video camera.

A variety of physical processes on different scales have to be considered for such a simulation. The very hot arc loses energy via electromagnetic radiation that is partially transmitted through the surrounding gas to the enclosure of the interruption chamber. There, it heats and vaporizes the wall material, causing it to be ejected into the chamber. Ions generated in the arc also heat the surfaces, and cause vaporization, of the metallic contacts. This metal vapor then mixes with the gas components in the chamber.

Simulation of such a complex multi-physics and pan-scale process is not trivial and years were dedicated to physical and numerical research to come up with suitable computational methods. Progress has benefitted from the rapid advance in computing hardware: Calculations are now often carried out on multicore workstations or on high-performance computing clusters. All this has resulted in the successful simulation of arcing in several types of circuit breaker.

> The conditions in the arc and its vicinity are extreme: The arc temperature easily exceeds 20,000 °C and sometimes the pressure in the interruption chamber reaches 70 bar.

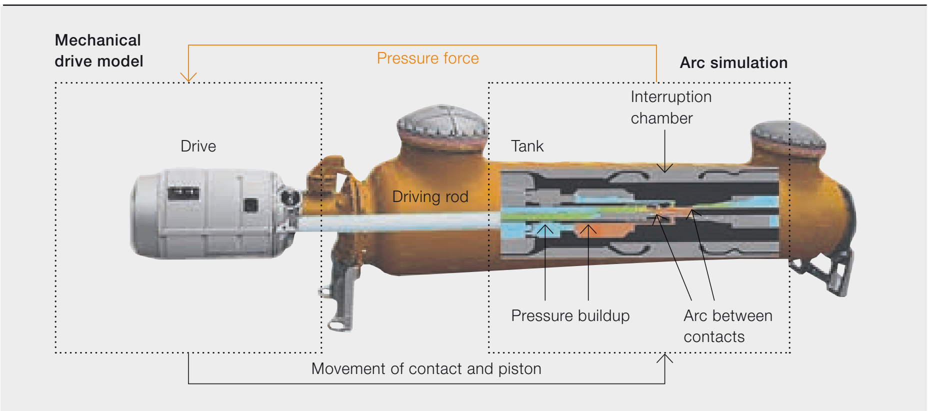
Generator circuit breakers

The world's largest SF_6 circuit breaker is ABB's HEC 9 generator circuit breaker. It is able to interrupt as much as a 250 kA rated short-circuit current, making it suitable for power plants up to 1.8 GW. On operation, an enormous amount of energy is released by the arc into the interruption chamber in a very short time. This generates huge pressures that are determined by the arc current, but also by the arc voltage, which, in turn, depends on the arc shape and temperature. As the pressure generated can be destructive, it is necessary to precisely simulate the flow conditions and the electromagnetic forces that influence the shape of the arc. Of equal importance is the simulation of the emitted radiation, because this is the major arc cooling mechanism.

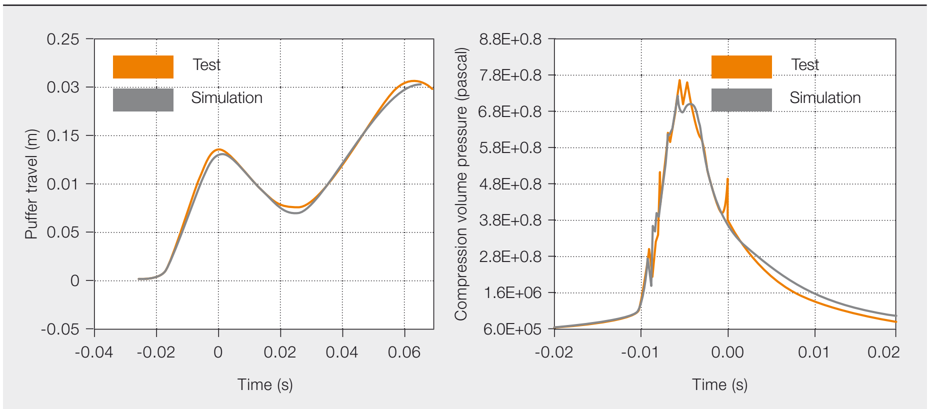
In a HEC 9 interruption chamber, a plug connects the electric contacts when the breaker is in the closed position → 1. The arc is ignited between the plug and the right-hand contact at the moment the plug moves out and disconnects from this contact → 1a. The arc then commutes from the plug to the left-hand contact when the plug disconnects from the left-hand contact. The circuit breaker is in the fully open position after the plug is completely out. Then, the arc burns between the two contacts → 1b. Note that the arc is

Simulations of the arc and its physical effects in the interruption chamber are of fundamental importance for the development of circuit breakers.

2 HV gas circuit breaker simulation



2a Arc simulation coupled with drive mechanical simulation



2b Comparison of test and simulation in pressure buildup in compression volume and in puffer piston travel

not axially symmetric; it fluctuates and forms loops, especially around current zero. Consequently, the arc voltage and the pressure in the interruption chamber fluctuate too.

Simulations of this situation give pressures that agree to within 10 percent of measured values.

Mechanical co-simulation of HV gas circuit breakers

High-voltage circuit breakers (HVCBs) are used to protect and control HV power transmission networks. Power levels and short-circuit currents are not as extreme as those seen in generator circuit breakers, but the electric field quickly reaches very high values after interruption. During the dielectric recovery, the hot gas between the arcing contacts has to be removed quickly by a strong gas flow if the electric field is not to cause problems.

ABB offers HVCB technology up to 1,100 kV, with rated breaking short-circuit currents up to 90 kA. For the prediction of a dielectric breakdown due to the high electric fields described, it is necessary to simulate the gas temperature and the gas density, as well as the electric field, shortly after current interruption. For this purpose, it is important to be able to predict the position of the electrodes precisely, bearing in mind that the interaction of the arc-generated pressure and the drive, which is mechanically coupled to the pressure chamber, determines electrode movement.

For current interruptions of this type, ABB invented the self-blast principle → 2. The idea is to use the thermal energy of the arc itself to build up a high-pressure, but comparatively cold, gas to blow out the arc.

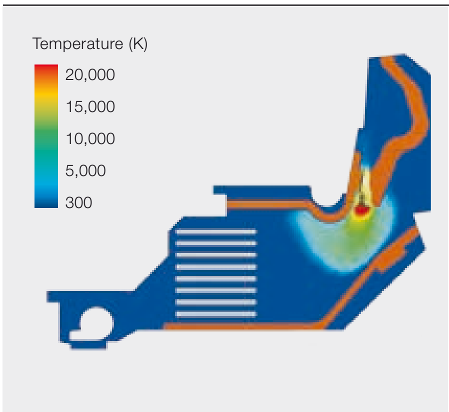
During the switching operation, the pressurized, heated gas mixes with the cold gas in the pressure chamber and this mixture flows back to the arcing zone to ensure the successful interruption of the electric current and dielectric recovery between the arcing contacts. The whole process takes 10 to 40 milliseconds. By using the fully coupled simulation of the arc physics and the mechanical drive, it is possible to predict the pressure buildup, arc voltage, gas mixing in the fixed volume and the flow pattern in the entire device accurately – information that is crucial for design and development of circuit breakers.

Further, because the pressures generated in the chamber can physically slow or reverse the contact movement, the movement is augmented by hydraulic or spring drives. The mechanical co-simulation described allows a drive to be designed that is not over-specified but that still fulfills all customer and type-test requirements regarding separation speed.

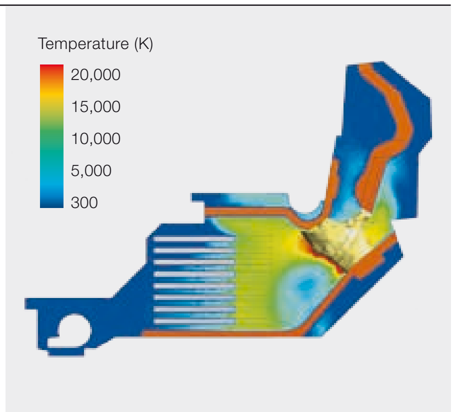
Moving arcs in low-voltage circuit breakers

Surprisingly, low-voltage circuit breakers are, in some ways, the most difficult to simulate. Here, further phenomena such as arc motion along rail electrodes, the interplay of ferromagnetic materials with arc-generated magnetic fields and the interaction between the arc and the external circuit have to be taken into account. The last phenomenon is especially important as low-voltage circuit breakers are inherently current-limiting. They build up a voltage that is comparable to the system voltage, thereby keeping the electric current below critical values and allowing for

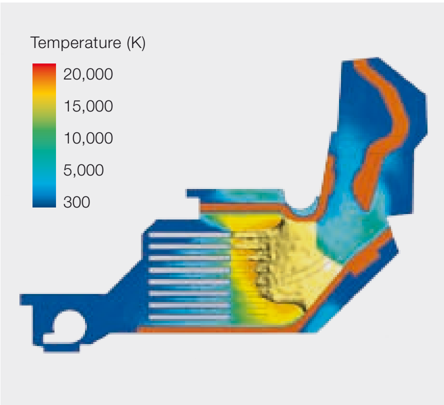
3 Transient simulation of a low-voltage short-circuit test. Gas temperature: blue to red. The arc is a white-yellow iso-surface for current density.



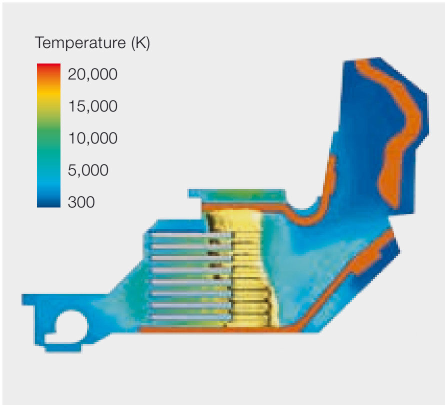
3a



3b



3c



3d

It is necessary to precisely simulate the flow conditions and the electromagnetic forces that influence the shape of the arc.

an interruption well before the natural zero crossing of the current.

Current limitation is achieved by increasing arcing voltage. This is done by ablating the polymeric housing materials and by splitting the arc into segments. By ablating the wall material, cold gas is added to the plasma, reducing its temperature. The cooling is improved further by splitting the arc into segments and allowing a larger metal surface area to absorb the energy emitted by the arc. Splitting can only be achieved if the arc can be transferred from its ignition point to the arcing chamber. This is done by employing the arc's self-generated magnetic field to drive the arc away from the nominal contacts. The driving force is increased by ferromagnetic material (usually steel plates) that concentrate and strongly enhance the magnetic field.

Simulating an arc in a low-voltage circuit breaker means following a fast evolution from ignition at electric contact separation ➔ 3a, over commutation from the nominal contacts to the arc runners ➔ 3b, along an electromagnetic force and pressure gradient driven run ➔ 3c, up to extinction in a rack of metallic plates where the arc plasma is split into fragments and cooled down ➔ 3d. The successful interruption of current in a low-voltage circuit breaker thus depends on a complex interplay of many physical phenomena taking place in the span of a few milliseconds. The simulation shown here is from the recent development of the ABB DSN200 electronic residual current circuit breaker with overload protection.

Outlook

Simulations of electric arcs are frequently used to support product design of circuit breakers and, in many cases, replace experiments that are very expensive, time-consuming or even impossible. But experiments cannot be replaced entirely. More elaborate physical models, faster computational methods and a better material understanding are all required to reach that goal.

Apart from support of product design, arc simulations greatly increase physical understanding of the process. In the future, these deeper insights will support the creation of new concepts for current interruption.

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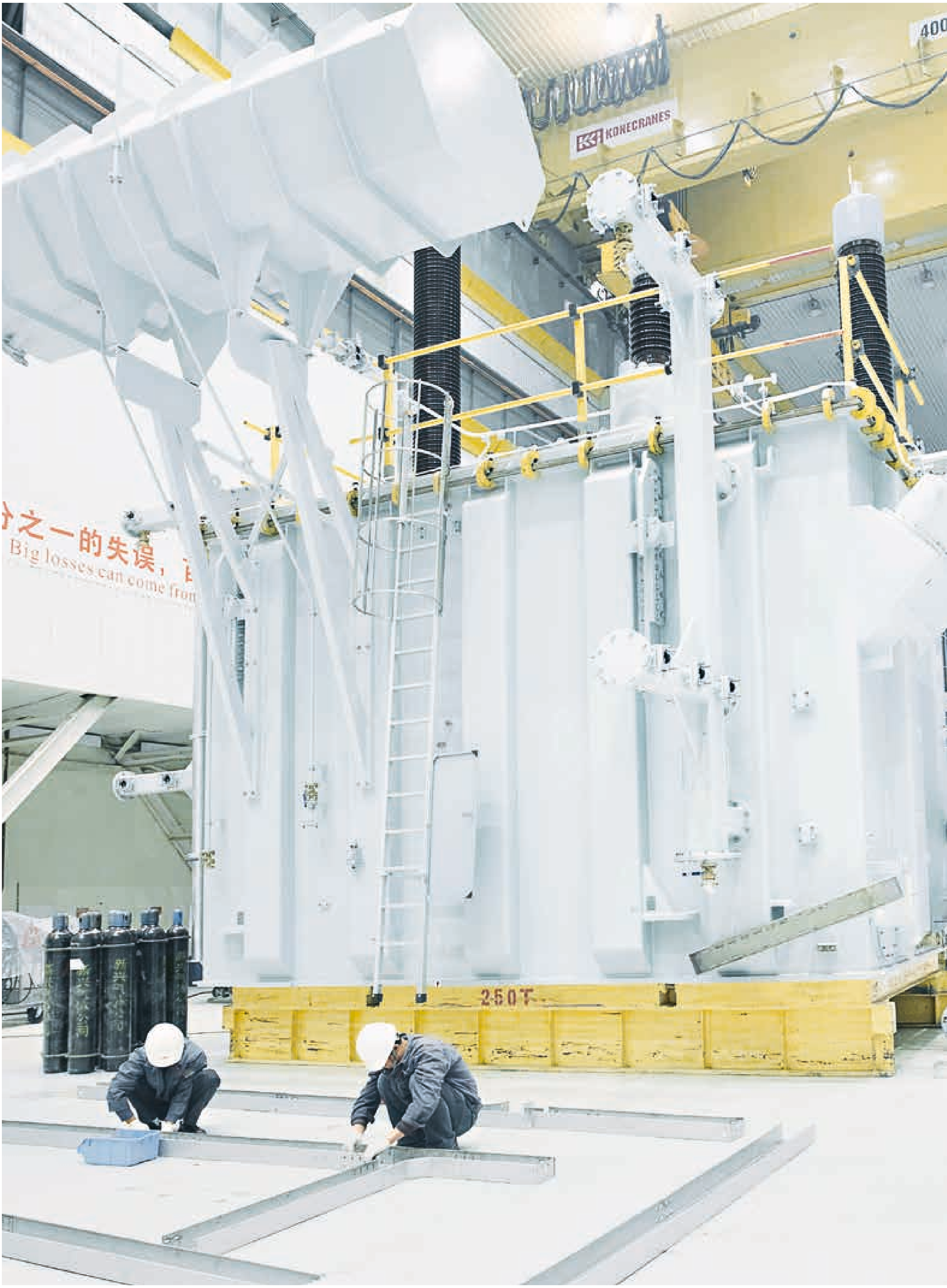

KONECRANES
2-50 T
Big losses can come from

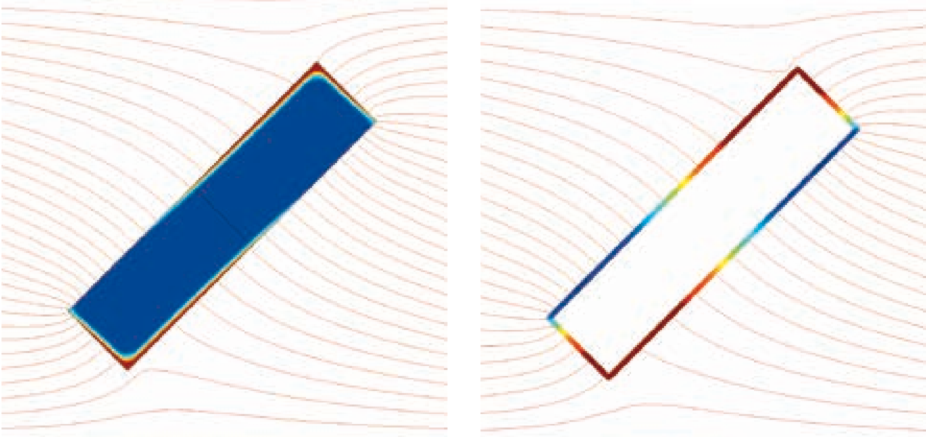
Picture perfect

Electromagnetic simulations of transformers

DANIEL SZARY, JANUSZ DUC, BERTRAND POULIN, DIETRICH BONMANN, GÖRAN ERIKSSON, THORSTEN STEINMETZ, ABDOLHAMID SHOORY – Power transformers are among the most expensive pieces of equipment in the entire electrical power network. For this reason, great effort is expended to make the design of transformers as perfect as possible. Invaluable tools in this endeavor are simulation software packages that are based on the finite element method. Simulation software not only predicts the effects of basic physics, but it also provides a way for ABB's century of experience in transformer design to be used in the design and exploited to the fullest. This is important as different types of transformers present different challenges in terms of magnetic flux loss mechanisms, complex nonlinear behavior and idiosyncrasies of physical design. All these factors must be accommodated while keeping computational overhead within reason.

Title picture
Simulating the detailed electromagnetic behavior of transformers is essential for good product design.

1 Loss distribution of the steel plate for rotation angle 45 degrees



1a Computed by resolving the interior

1b Computed by SIBC technique

Nonlinear material properties and device complexity are two significant factors that drive the computational horsepower required for the software simulation of both oil-immersed and dry-type power transformers. However, a deep knowledge of power transformer design allows very accurate simulations to be made without running up against computational limits.

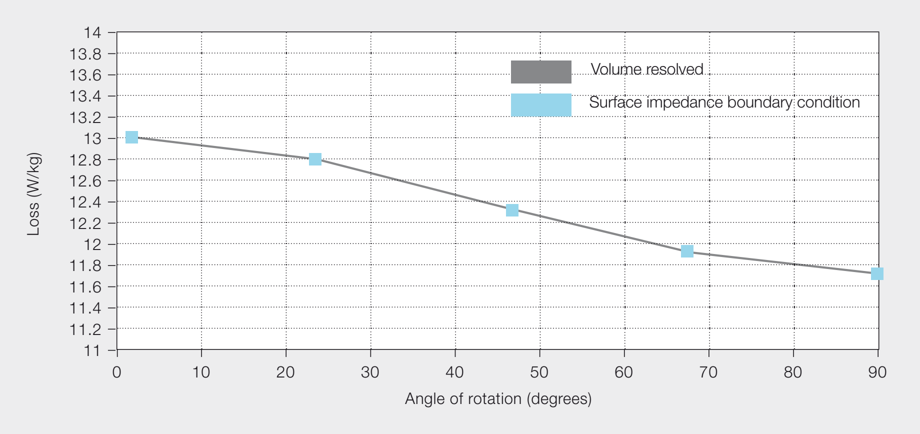
An accurate calculation of stray losses and their spatial distribution requires appropriate numerical models for the loss mechanisms in the construction materials themselves.

Power transformers have a critical task: They must step the voltage up and back down on the way from the power plant to the final consumer. In a perfect world, they would be 100 percent efficient, but in reality, every transformer generates losses. In general, the so-called load losses in transformers have three components: resistive and eddy-current losses that appear in windings and busbars, and stray losses that are generated in the metallic parts of transformers exposed to magnetic fields, eg, the tank, core clamping structures and tank shielding. This unavoidable leakage of magnetic flux not only represents a loss of energy, but can also cause local thermal hot spots and thus shorten the life of the transformer.

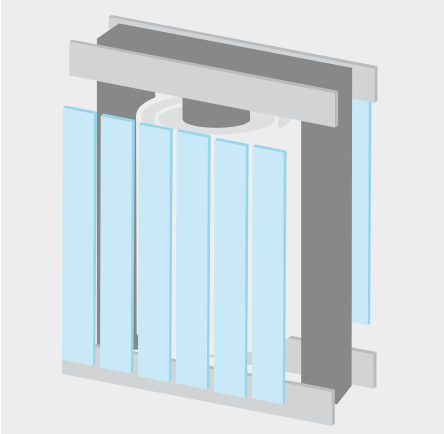
Whereas resistive and eddy-current losses can be accurately calculated by 2-D simulation, the calculation of stray losses outside the windings is a complex 3-D problem and a suitable transformer model is necessary to solve it. This model can be created by simulation software suites that are based on the finite element method. Finite element analysis (FEA) is a sophisticated tool widely used to solve engineering problems arising from electromagnetic fields, thermal effects, etc. In FEA, using smaller element sizes yields higher, and thus better, resolution of the problem, but also increases the computational power required, so a balance must be struck between element size, degree of model detail, approximation of material properties, computing time and the precision of the results.

Simulation software can resolve the basic electromagnetic field situation by solving Maxwell's equations in a finite region of space with appropriate boundary conditions (current excitation and conditions at the outer boundaries of the model). However, the rest of the simulation depends on the input of the user. This is where ABB's long experience in transformer design bears fruit.

2 Simulated total loss in the plate as a function of rotation angle. The SIBC technique gives results very close to those obtained by resolving the entire volume.



3 Geometry of the power transformer simulation model (tank not shown)



Simulating stray loss

An accurate calculation of stray losses and their spatial distribution requires appropriate numerical models for the loss mechanisms in the construction materials themselves.

Losses are significant in solid materials, but also in laminated materials, such as laminated steel, since stray fields are, in general, not restricted to the plane parallel to the lamination planes. In addition to eddy-current loss, there is also hysteresis loss in ferromagnetic materials due to microscopic energy dissipation when the materials are subjected to oscillating magnetic fields. Furthermore, in order to compute the total loss distribution accurately, the model has to take into account the nonlinearity of the magnetization curve. This nonlinearity not only influences the magnetic field distribution but also, indirectly, the eddy current distribution. The high degree of anisotropy in laminated steel introduces additional complications that must be taken into account.

The so-called skin effect also complicates matters: Eddy currents induced close to the surface of a metallic object tend to have a shielding effect, resulting in an exponential decay of fields and current towards the interior of the object. This skin effect becomes more pronounced as conductivity and permeability increase, implying that, in typical materials of interest, the characteristic decay length ("skin depth") is of the order of a millimeter or less. As a consequence, the losses are concentrated in this thin layer. At first sight, it seems necessary to resolve the skin depth layer into several finite elements in order to compute the loss – a procedure that would require excessive computer power for a full 3-D simulation. Fortunately, one can employ surface impedance boundary conditions (SIBCs) to significantly reduce the solution volume and thus the computer power requirements. Here, the interior of the metallic object is removed from the computational domain and the effect of eddy currents flowing close to its surface is taken into account by specifying analytically the surface impedance – ie, the ratio between electric and magnetic fields at the surface.

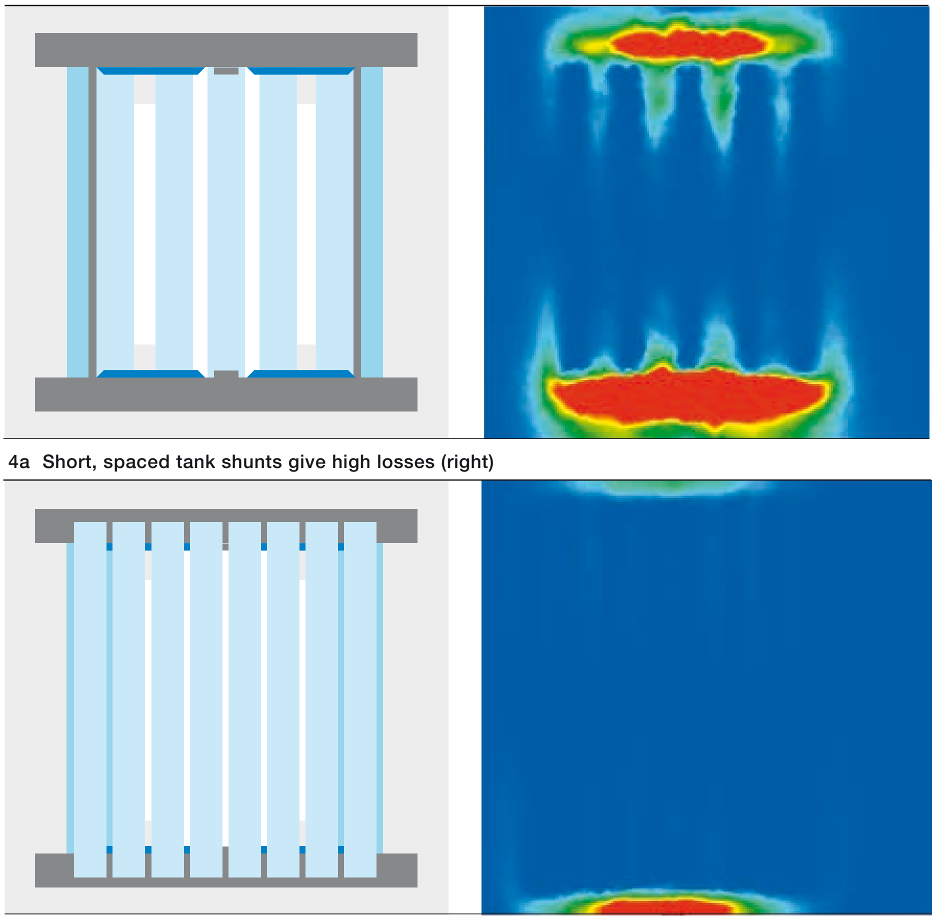
The usefulness of the SIBC method can be illustrated. An infinitely long steel plate with a 12 × 50 mm cross-section and skin depth of 1 mm at 50 Hz can be simulated at various rotation angles in a magnetic field. The total eddy-current loss is computed using a full volume resolution of the plate interior (requiring 4,220 finite elements for the entire computational domain) → 1a and an SIBC formulation (requiring 1,674 finite elements) → 1b. The SIBC yields a virtually identical loss value compared with the full volume case → 2. The relative gain in using SIBC is significant even for this small object and as the size increases the relative gain is magnified.

At ABB, different numerical techniques for computing loss distributions in transformer construction materials are being evaluated and improved. The objective is to find the most accurate models that can be used in 3-D simulations while keeping computational overhead reasonable. This is accomplished by combining carefully controlled experimental measurements on test objects with detailed simulations.

Different types of advanced numerical simulations, usually based on FEA, are applied to develop and improve dry-type transformer technologies and products.

The objective is to find the most accurate models that can be used in 3-D simulations while keeping computational overhead reasonable.

4 Influence of the tank shunt geometry on the distribution of the losses generated in the transformer tank



4a Short, spaced tank shunts give high losses (right)

4b Longer, closer-spaced tank shunts result in lower losses (right)

Different suggested loss modeling techniques for nonlinear and/or laminated materials are then evaluated based on these results.

Electromagnetic simulations of oil-immersed power transformers

The windings in autotransformers (an ABB 243 MVA single-phase 512.5/230/13.8 kV type is used here for illustration) tend to produce high amounts of stray flux relative to their physical size. This implies potentially high stray losses and possible hot spots in the transformer tank. However, with appropriate simulation and design, a tank shielding can be produced that avoids this. In the case shown here, magnetic shunts mounted on the tank wall were employed as shielding. Shunts are ferromagnetic steel elements that guide the flux emanating from the transformer winding ends.

The 3-D FEA model included all the important constructional parts necessary to carry out the magnetic simulations and loss calculations ➔ 3. Because of the complexity of the real transformer, some simplifications were introduced to make the computational load more managable.

In the initial design, where the tank shunts are too far apart and of insufficient height, loss densities were significantly higher directly opposite the active part, relative to other areas of the tank ➔ 4a. The critical regions exposed to magnetic field impact are clearly visible in the figure – mainly above and below the magnetic shunts. Several design iterations increased shunt height and number, and decreased spacing. The losses generated in the tank consequently decreased by almost 40 percent. The simulations allowed the required performance to be attained while minimizing the extra material, and thus costs, involved ➔ 4b.

Electromagnetic simulations of dry-type transformers

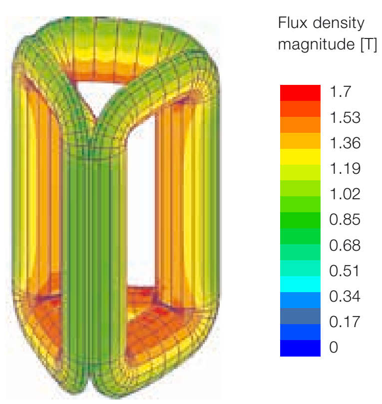
The active part (consisting of the main parts: core, windings, structural components and leads) of a dry-type transformer is not immersed in an insulation liquid, in contrast to oil-immersed power and distribution transformers. Both electric insulation and cooling of the active part are performed by ambient air. Different types of advanced numerical simulations, usually based on FEA, are applied to develop and improve dry-type transformer technologies and products.

TriDry – dry-type transformers with triangular wound cores

In contrast to conventional transformers with planar-stacked magnetic cores, the three-core legs of the TriDry experience identical magnetic conditions ➔ 5. Numerical simulation of the magnetic fields in the core are particularly challenging because an anisotropic material model is required as the permeability is very high parallel to the laminations but much lower in the orthogonal direction ➔ 5. These simulations give fundamental insight into the magnetic behavior of the TriDry transformers. Also, detailed analyses of the emitted stray field intensities of TriDry transformers can be performed by numerical simulations. These can be required to ensure legal compliance – for example, to the 1 microtesla RMS limit for transformers installed in Switzerland in sensitive areas.

5 TriDry transformer and the simulated magnetic flux density distribution in its magnetic core.

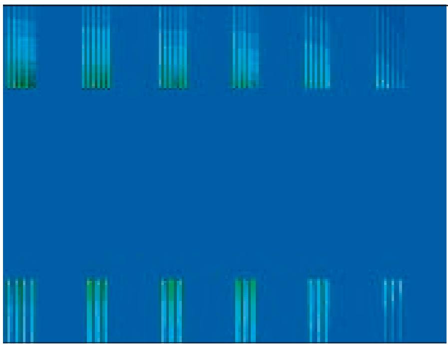
5a TriDry transformer



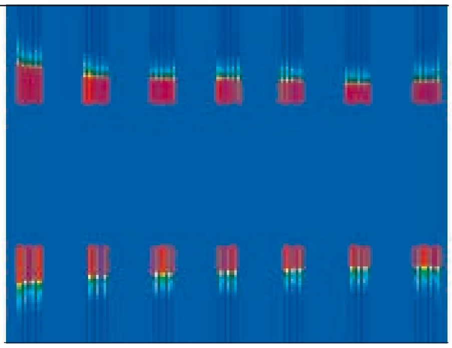
5b Magnetic flux density distribution

Surface impedance boundary conditions (SIBCs) can significantly reduce the solution volume and thus the computer power requirements.

6 Electromagnetic simulations of a 12-pulse transformer; winding loss distribution over the end sections of the foil conductors



6a At the fundamental frequency



6b At the fifth harmonic frequency

Dry-type variable-speed drive transformers

Variable-speed drive transformers are used to supply AC motors. The power electronics associated with these transformers generate current harmonics that increase winding loss, potentially leading to hot spots. This must be taken into consideration when constructing simulation models. A typical example of winding loss simulation is shown in → 6. Here, the relative winding loss distribution over the end sections of the foil conductors of the two opposite winding blocks is shown for a 12-pulse transformer with two secondary windings. The winding loss at the fundamental frequency is more uniformly distributed along the conductor surface than the winding loss of the fifth harmonic frequency. This is because the currents of the two secondary windings are in phase at the fundamental frequency, resulting mainly in axial flux. However, these currents are in opposing phase at the fifth harmonic frequency, resulting in a radial flux that concentrates losses in the winding region near the axial gap between them. This causes hot spots, requiring the design to be amended accordingly.

Simulation success

Numerical simulation of electromagnetic fields have proven to be a very powerful tool in the development and design of today's transformers. Appropriate numerical models facilitate, for instance, the simulation of stray losses in structural components, winding losses or core magnetization – applicable to different types of transformers.

The numerical simulations described here are used in research, development and engineering by ABB and they make a significant contribution to ABB's high-quality oil-immersed and dry-type transformer products.

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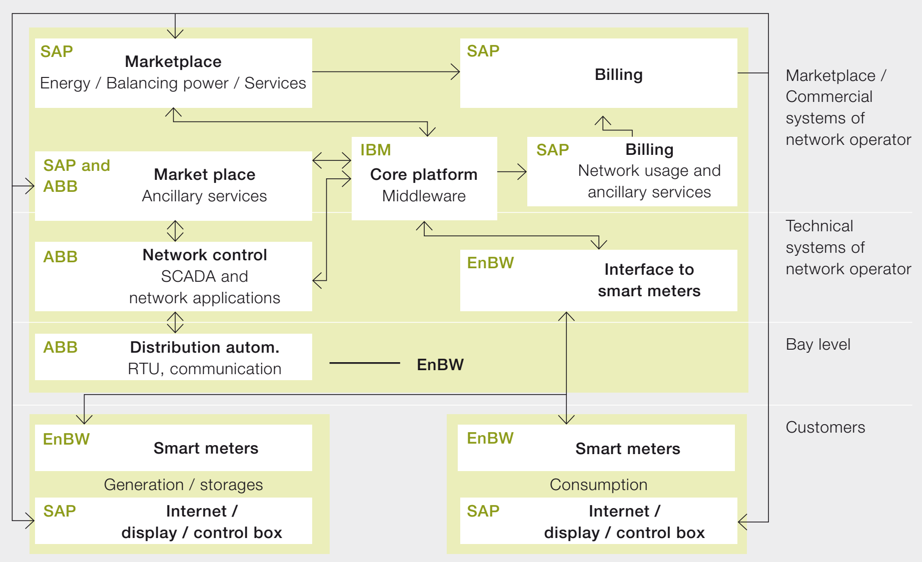
Head smart

Strengthening smart grids through real-world pilot collaboration

CARSTEN FRANKE, TATJANA KOSTIC, STEPHAN KAUTSCH, BRITTA BUCHHOLZ, ADAM SLUPINSKI – ABB has, and continues to develop, all the necessary components to enable and optimize smart grids. In order to evaluate and further improve existing solutions, ABB participates in research projects and pilot installations. One of these very successful pilot projects was the MeRegio pilot, one of six beacon E-energy projects funded by the German government. ABB's development of new information and communication technologies for smart grids, required extensive cooperation work with numerous project partners. The outcome is a solution that brings yet further strength and stability to smart grids.

1 Consortium and competency interactions in MeRegio



In 2012 ABB successfully completed its participation in the MeRegio (Minimum Emission Region) pilot project. The pilot, which started in 2008, is one of a group of E-energy projects that are funded by the German government's Federal Ministry of Economics and Technology in partnership with the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [1].

Like all of the E-Energy projects the focus of MeRegio was on developing, implementing and testing information and communication technology (ICT) for managing future energy systems. The MeRegio project consortium comprised:
- ABB
- EnBW Energie Baden-Württemberg
- IBM Deutschland
- SAP
- Systemplan GmbH
- University of Karlsruhe (KIT)

The responsible parties and their main components are shown at → 1. ABB was mainly responsible for the network control and the distribution automation. IBM focused on the information exchange middleware to connect the various MeRegio components. SAP mainly developed the marketplace while EnBW, as the utility, developed the platform for smart meters and control box integration into their grid.

Furthermore, EnBW led the overall consortium. KIT supported the consortium with specific research tasks. Systemplan helped to set up and install submeters specifically for industrial customers.

New ICTs for smart grids

Within MeRegio, ABB developed and installed new, intelligent measuring devices and techniques. However, the main focus of the ABB contribution was on developing and deploying new information and communication technologies embracing additional network control applications and mechanisms in smart grids. ABB focused specifically on four different development aspects. Subsequently aspects one, three and four have all been evaluated through intensive simulations.

> Secondary substations can almost double the amount of renewable power generation that can be integrated.

Aspect one: offline simulations

The first aspect that was investigated in detail within the MeRegio project focused on offline simulations for the pilot medium- and low-voltage network in order to identify further optimization opportunities. Therefore, ABB took into account different new technical solutions, like cos(φ) regulation, voltage regulation units and energy storage. Results from this work are, for example, that voltage regulations in the secondary substations can almost double the amount of renewable power generation that can be integrated and avoid voltage band violations in the low-voltage grids without any modification of the network topology. Furthermore, it has been ensured that all these offline simulation results can also be applied for other grids. Therefore the acquired knowledge can be reused and can help customers with similar issues. In addition these results have been used to identify scenarios where the installation of additional ICT for further investigation, monitoring, and increase in reliability of supply in the distribution grid, is meaningful.

Aspect two: development of measuring technologies

Based on this knowledge the second aspect focused on the further development of measuring technologies for secondary substations. This required the use of remote terminal units (RTUs) to automate the operation of secondary substations. For the realization, the ABB RTU560 and the Multimeter 560CVD11 were used in order to determine the voltage on the medium-voltage side of the substation by only using

Title picture
The model region of Freimat in Germany.
Photo © 2013 Luca Siermann.

measurements from the low-voltage side. This specific measuring technique was developed within the MeRegio pilot and was also intensively tested in the field network. As this approach to determine the medium side voltage has now been proven to work well, it has already been applied in subsequent ABB pilot projects.

Aspect three: integration of measurements

The third aspect that was realized within the MeRegio project focuses on the integration of all medium- and low-voltage measurements from the different substations as well as the use of the available smart meter measurements in the network management system. In this way, the network calculations can be enhanced and the network operator has better online control capabilities. Whereas the data from the substations could be integrated directly using existing communication protocols, the smart meter data import called for a newly developed mechanism. The required data exchange has been implemented via a Web-service interface with the IBM CORE platform using a data model that was highly influenced by existing standards. Specifically the Common Information Model (DCIM, including extensions for distribution, IEC 61968-11 and IEC 61970-301) has influenced the information model exchange protocol, which was developed by ABB. The integrated data from the low- and medium-voltage levels makes it possible to run power flows and to visualize network bottlenecks and voltage violations. For this, a coloring approach has been used to also show the load- and generation-dependent influences relating to the identified problems. All of these concepts and methods have been validated by executing intensive system simulations.

Aspect four: market-compliant approach

The fourth aspect of the MeRegio pilot focused on the market compliant approach to Demand Side Management applied to the medium- and low-voltage grids. Here, ABB implemented forecasts for decentralized photovoltaic and wind based generation. Furthermore, an additional interface to the IBM CORE platform was implemented to receive the forecasts from special "control boxes" installed within the given distribution grid that is operated by EnBW. Based on all these data, predictive power flows have been implemented in order to anticipate potential network bottlenecks up to six hours in advance. The results of these predictive calculations are encoded in XML and communicated to an analysis tool. This newly generated bottleneck analysis module calculates, for all loads and all generators, sensitivities to expected problems. Based on these sensitivities, the module actively suggests re-dispatch schemes involving the local generation and loads. These solutions are encoded in so called priority signals that are communicated towards the marketplace of the distribution system operator in order to be resolved. The priority signals data exchange model has been developed as an extension to standard DCIM. This ensures that similar problems in distribution grids can be solved in a very similar way using the same message payload types. The whole problem, starting from the predictive load flow, including the bottleneck analysis, the sensitivity signal's generation and communication was addressed by a team of experts from ABB.

Network bottlenecks were simulated because of the difficulty of observing such events frequently enough in real life.

The evaluation of the effectiveness of the "priority signal" process to proactively resolve expected network bottlenecks was primarily based on online simulations of the distribution grid. This reflects the difficulties of observing such bottlenecks frequently enough in the real life system. Therefore, some loads and generation forecast data were modified in order to generate bottlenecks for different lead times. Then the algorithms and information exchange mechanisms were evaluated regarding their efficiency at identifying and resolving the predicted network problems.

Demonstrable results

The pilot evaluation itself was based not only on field measurements but also on extensive simulations. In order to demonstrate and communicate the outcome of the MeRegio pilot project to a larger audience, a sophisticated demonstrator, the ABB Smart Distribution System, has been developed that can be used to introduce and demonstrate smart grids in general and further explain the MeRegio issues and the developed solution strategies. Additionally, the demonstrator also addresses the evaluation of economic impacts of smart grid solutions to given network operation problems. Simulation was a critical part of developing the solution shown in the demonstrator, however the project could only have been successful when many parties worked together to share their expertise and ideas. Such successful collaboration is an example of how it is possible for different interest groups to work together to bring the world a solution that has benefits for everyone. Two (or more) heads really are better than one.

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Making sense

Designing more accurate and robust sensors through system and multiphysics simulation

ROLF DISSELNKOETTER, JÖRG GEBHARDT, ROSTYSLAV TYKHONYUK, HOLGER NEUBERT – Instrumentation is a critical element of many of ABB's businesses. To keep pace with rapidly evolving requirements, the company is taking a leading role in sensor technology research, seeking to develop new sensing technologies, decrease sensor footprint, fulfill new standards and develop innovative applications. With these goals in mind, ABB is using system and multiphysics simulation to successfully develop more accurate and robust sensors.

1 von Mises stress distribution caused by an external static torque

Deformations exaggerated by a factor of 1,000

Sensor development is quite often characterized by high requirements in accuracy. In fact, some applications require accuracies of up to 0.1 to 0.05 percent of the measured value.

Sensor technologies often show nontrivial system-level effects, eg, because of design details or the number of components whose behavior influences the measurement chain. Internal and external influences (eg, thermomechanical, chemical, electromagnetic crosstalk) may cause unwanted drift of gain, phase and offset, and may deteriorate the accuracy and stability of the measurement signals.

Full system simulations or multidomain physical simulations can be used to avoid cumbersome tests on a number of physical prototypes, and to obtain a reliable high-accuracy prediction of device performance. Sensor design, therefore, is a prime example of model-based mechatronics development, described, eg, in [1]. Examples of these two simulation cases follow.

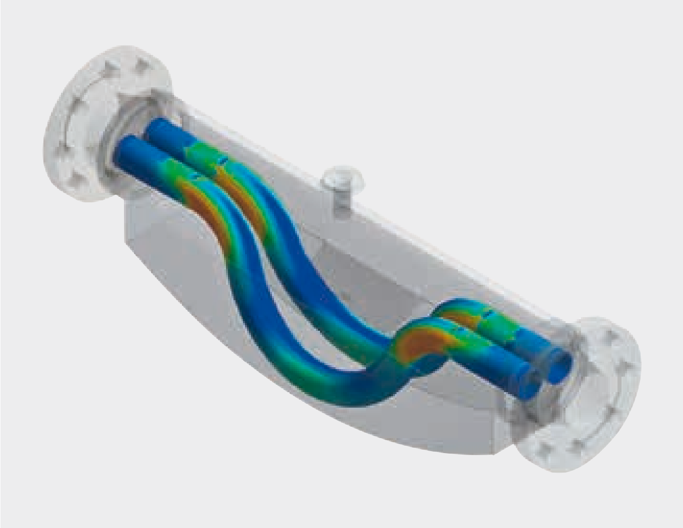
Title picture
The FCB 350 Coriolis flowmeter (DN25)

Coriolis flowmeters

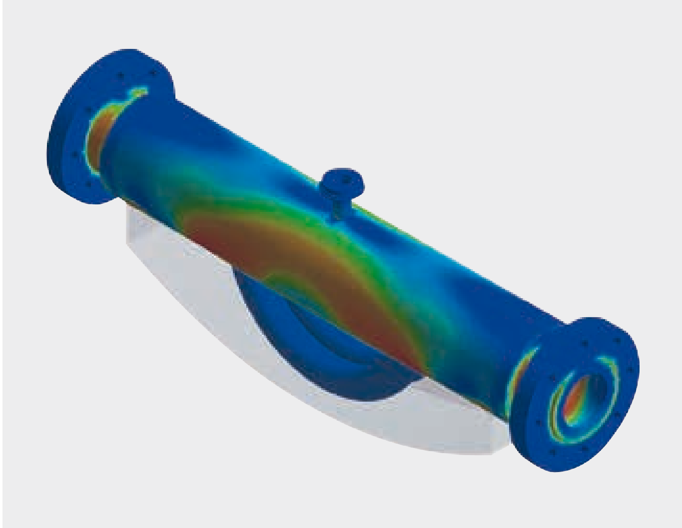
A Coriolis sensor is a system with strongly interacting components. When the drive unit is supplying an AC current to an actuator on the flow tubes, they will vibrate. Due to the Coriolis effect, fluid flow through the tubes will generate small phase shifts between the vibrations at different locations in the mechanical system. This is detected by means of two vibration sensors placed at different locations. The electronics evaluates the phase shift between the two sensor signals and uses their amplitude to control the drive current.

Not only is profound theoretical know-how required in the design of Coriolis flowmeters, but the R&D methodology must be highly efficient.

Not only is profound theoretical know-how required in the design of Coriolis flowmeters, but the R&D methodology must be highly efficient. It has to enable the design of complete product lines,



2a Operational eigenmode: deformations and stress distribution



2b Stress distribution for the lowest eigenmode of the device´s housing

and of customer-specific product variations. Quantitative design criteria, which can be operationalized in virtual and experimental tests, form the basis of excellent development results.

Sensitivity and cross-sensitivity

Exact numerical prediction of flow sensitivity has two important purposes: First, it enables analysis of external influences according to their actual effect on the measurement process, and in this way minimizes unwanted cross-sensitivities and optimizes the design. Second, the same range of output signals is common to the entire range of meter sizes, and thus optimizes the signal processing algorithms.

Mechanical robustness and dynamic stability

All measurement signals generated by the device must be stable under a number of inevitable and potentially erratic environmental influences.

An important performance and device stability criterion, which can be efficiently tested by simulations, is given by density measurement under various external loads. As a first calculation step, a typical worst-case load is applied to the device. ➔ 1 shows the nonlinear response of the structure for a specific external load. The result of this step is also used to determine mechanical device robustness.

In a second step, eigenfrequencies of the system are calculated, as shown in ➔ 2a. For a design to pass this test, it is important that load-induced frequency shifts do not violate the accuracy requirements of the device.

Further, a decoupling of the operational vibrations from the outer shell of the device is important. By choosing special design parameters, the operation mode will be well separated from the modes of the outer surface. An example of the latter is shown in ➔ 2b.

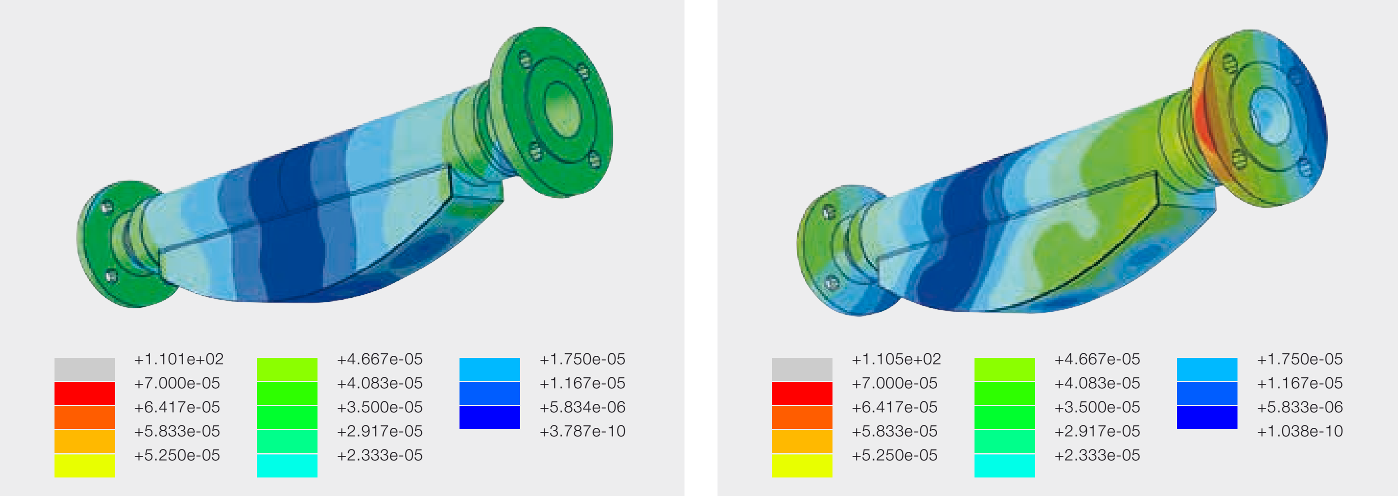
Robust design for performance reliability

For high-quality flow measurement, the main variable to be controlled is the “zero phase,” the integral measure for the influence of superimposed manufacturing tolerances and asymmetries, which lead to a nonzero signal without flow. It is particularly challenging to reduce time-dependent physical influences on the zero phase, as this can lead to errors in the measurement result, which cannot be compensated. External damping elements may touch the device at any position on its outer hull, which is vibrating due to the meter´s operating principle. In such a case, energy is extracted at that position, leading to a low-amplitude change in the traveling wave structure in the device. The internal and external mechanical setup of a Coriolis meter must be carefully chosen to keep this influence small, in particular with respect to the consequences on the motion of the sensor tubes and signal pickups.

Algorithms have been developed that allow a highly efficient calculation of zero phases as a function of local damping –

Exact numerical prediction of flow sensitivity enables analysis of external influences according to their actual effect on the measurement process and optimizes the signal processing algorithms.

3 Contour plots of zero phases (in degrees), induced by a damper of given constant strength, as a function of damper location



3a In absence of preloads (no external static forces applied)

3b Under a strong external static load (axial torque)

ie, damping strength and damper location. This is a special numeric challenge as well, since the phases to be calculated are exceptionally small – in the range of 10^{-5} degrees.

→ 3a shows a contour plot of induced zero phases as a function of damper location for a given constant damper strength. The calculation result can be compared with the allowed limit of zero phases for the given flowmeter. → 3b shows the same situation when the system is put under a strong axial torque load. The result shows that, for this design, the zero phase remains stable at a very low value even for strong external influences.

For high-quality flow measurement, the main variable to be controlled is the "zero phase," the integral measure for the influence of superimposed manufacturing tolerances and asymmetries.

Finally, representative criteria have been selected that are efficient to use and reliably represent stable zero-phase behavior for the ABB CoriolisMaster product design. For a number of Coriolis meters, virtual drop-impact (ie, crash) tests are performed [2] via finite-element calculations with explicit time integration.

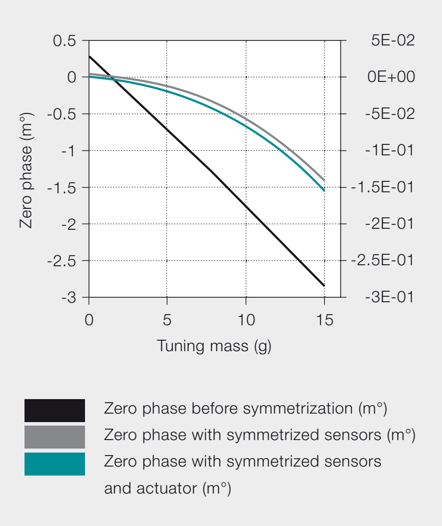
To arrive at a robust, low-cost design, sensitivity analyses with respect to inevitable manufacturing tolerances are performed. Flowmeter production can thus be tailored to achieve the highest customer value. In a robust design, the tolerances have less influence on performance [3] → 4.

Magnetic design in a system context

The couplings in a Coriolis sensor, which as mentioned has strongly interacting components, are indicated with black arrows in → 5. The included actuator and vibration sensors are based on the voice coil principle. This is comprised of a permanent magnet, a soft magnetic flux concentrator and a movable coil in the magnetic air gap. The force between the magnet and the actuator coil generates the vibrations that are measured through the voltage induced in the sensor coils.

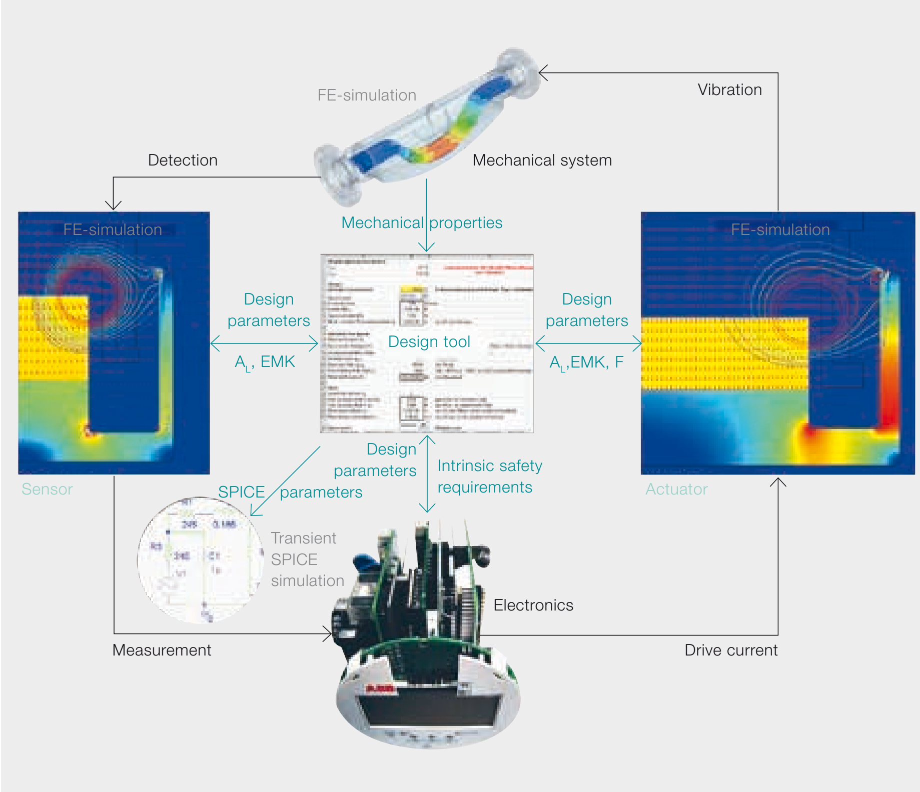
When designing and optimizing the magnetic components, the complete chain of interacting parts must be considered. The required sensitivities of the actuator and sensors, for example, depend on each other and on properties of the mechanical and electronic subsystems. In addition, boundary conditions like the maximum weight and size of the mag-

4 Zero phase vs. tuning mass



For the gray and green curves, the right y-axis, which is scaled up by a factor of 10, applies. The symmetrized design has a zero point that is much more stable under mass differences between the twin tubes.

5 Magnetic and electronic design process for the sensor-/actuator system



netic parts, and limitations of the electric impedances and signal amplitudes from intrinsic safety requirements, must be taken into account.

This is ensured by using a spreadsheet-based design tool, which enables collection and matching of the magnetic, electronic and mechanical data required. The tool provides an interface to the FE (finite-element) models of the magnetic components by exchanging design parameters and the resulting electromagnetic characteristics. Further, it gathers the results of the mechanical simulation and includes a simplified model of the drive circuitry. During the parameter optimization it monitors compliance with the design goals and boundary conditions by indicating any deviations. Thus, the design of magnetic components and drive circuitry can be developed in an iterative process. The tool can also output the parameters of a basic equivalent-circuit SPICE (simulation program with integrated circuit emphasis) model for the transient simulation of the drive, actuator and mechanical system. ABB has already designed several new Coriolis sensors using this tool and the implemented design process.

Electromagnetic sensors

Common electromagnetic sensors include current transformers (CT), position and proximity sensors. Although several simulation tools are suited for investigating such systems, special modeling techniques and solver settings are often required to obtain stable and efficient calculations and accurate results. Further, a reasonable compromise between model complexity and accuracy needs to be made.

> To arrive at a robust, low-cost design, sensitivity analyses with respect to inevitable manufacturing tolerances are performed.

Typical challenges with sensor simulation include:

- Complex 3-D geometry that includes details over a wide size range
- Nonlinear effects
- Hysteresis
- Transient behavior
- Cross-talk
- Coupling of physical effects that react on different time scales (eg, electrical and thermal)

In 2009 ABB began collaborating with the Dresden University of Technology to develop FE modeling techniques for electromagnetic sensors, which are applicable in different development projects. The focus is on 3-D models with coupled parameters (multiphysics models).

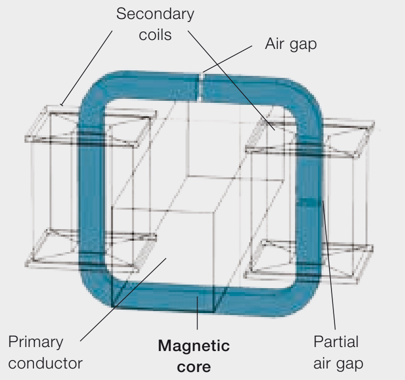
Sample system

→ 6 shows a geometry model that has been used in the investigations. Although this is not a real design, it has the typical properties of some types of current sensors.

It is a nonsymmetric 3-D model of a CT with a primary busbar and a secondary winding, which is split into two coils. The magnetic core has two different types of air gaps. The dimensions of the paramet-

When designing and optimizing the magnetic components, the complete chain of interacting parts must be considered.

6 Geometry of a transformer model



7 Electromagnetic sensor model features

- Nonlinear, anhysteretic magnetic characteristic H(B) of the core material. An analytic formulation has been chosen for best numerical stability.
- "Wire-bound" secondary current distribution in the coils modeled with eight prismatic bodies. Copper resistance is temperature dependent.
- Models are suited for transient simulation.
- Coupling with integrated SPICE circuit models (eg, current source, secondary load, closed-loop operation with additional flux-sensor).
- Induced eddy currents in the primary busbar leading to additional losses and to an inhomogeneous current-density distribution from the skin effect. The air gaps will cause sensitivity with respect to magnetic stray fields and the current distribution.
- Calculation of the conduction loss densities in the primary and secondary windings.
- Explicit and analytical modeling of laminated (stacked or strip-wound) cores.
- Dynamic hysteresis and electric loss distribution from eddy currents in the magnetic core.
- Integrated thermal model calculating the temperature distribution from the electric losses in the windings and the magnetic core. Temperature drift of electrical conductivities is considered in a closed-loop iteration process, controlled with an external program.

ric model can be modified, and it can be extended with a flux sensor in one of the gaps and with electric circuitry to form a closed-loop current sensor.

Based on this design, various model versions were developed to investigate different physical aspects. They enable modeling of the phenomena and their properties either separately or in combination.

Model features

The model in ➔ 6 presents several challenges: It is 3-D, nonsymmetric (ie, cannot be reduced to a subgeometry with suitable boundary conditions) and contains small details (ie, air gaps) in a large structure. These air gaps strongly influence the stray-field distribution and the properties of the sensor. However, without optimized geometry meshing they will lead to a large number of finite elements and long calculation times.

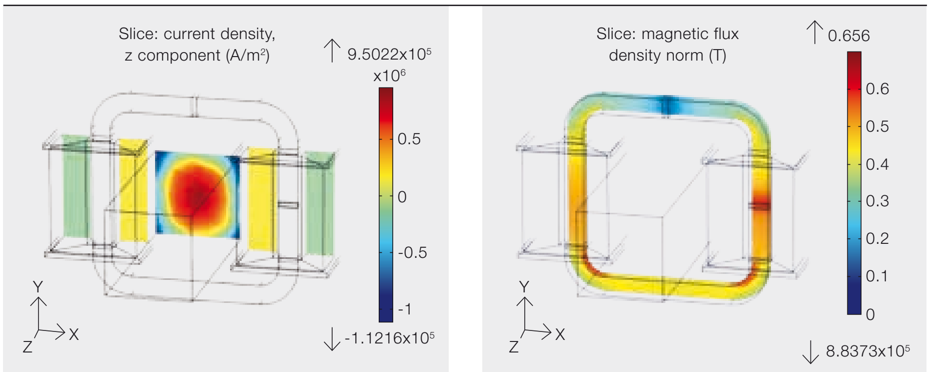
Additional features implemented in the models thus far are highlighted in ➔ 7. This list shows that, in a real sensor, there may be many physical effects and couplings. Which of these need to be considered in the analysis depends on the specific problem.

Special modeling techniques and solver settings are often required to obtain stable and efficient calculations and accurate results.

Results

Good progress has already been made on the models [4, 5]. ➔ 8 shows results obtained on a model version with a bulk copper busbar and a FeSi-based core material with a nonlinear magnetic characteristic. It is assumed to be electrically nonconductive. Therefore, there are no electric core losses and a nonlaminated core model can be made. The FE model is coupled to SPICE circuit models with a sinusoidal current source at the primary side and a load resistor at the secondary winding, which has N_{sec} loops. The loss distribution is calculated and used as input to the thermal simulation, which then yields the temperature distribution. Electric conduction is temperature dependent. Because of the nonlinear core characteristic and the coupling to a circuit model, transient simulation is required.

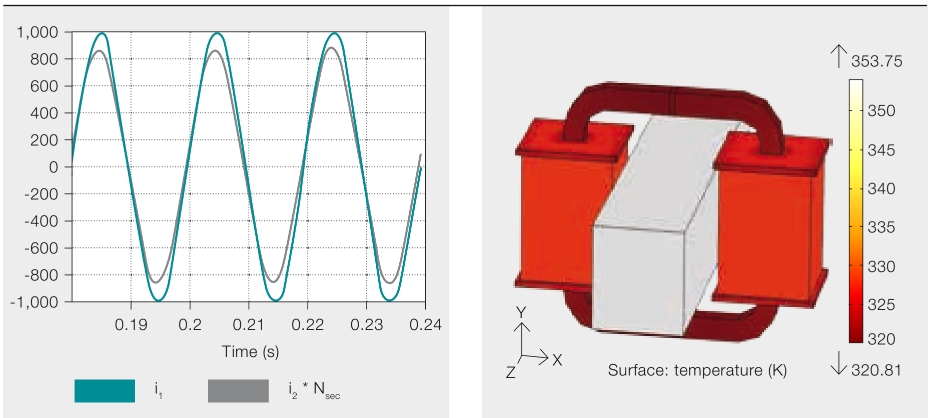
8 Current and magnetic flux-density distribution



8a Instantaneous current-density distribution (z-component) with skin effect in the primary conductor

8b Respective instantaneous magnetic flux-density distribution (absolute value) in the center plane of the transformer core

9 Current signals and temperature distribution



9a Primary and normalized secondary current showing an imperfect transformer coupling

9b Resulting stationary temperature distribution at the surfaces of the solids

→ 8 shows the resulting current-density distribution in the conductors at a specific point in time. Skin effect is visible and it can be seen that a reverse current is even flowing at the center of the busbar. The respective asymmetric core flux-density distribution is influenced by both the current distribution and the air gaps.

→ 9 shows the current signals, which do not match well and thus indicate an imperfect transformer coupling due to the air gaps. Further, the stationary temperature distribution shows the effect of the electrical conduction losses.

As research continues, ABB and its academic partners will focus on improved laminated-core models for higher frequencies, automatic calibration of the nonlinear magnetic characteristic, the implementation of different coil winding shapes, further improved SPICE modeling and experimental model validation.

Transforming technology for customers

System and multiphysics simulations are essential to gain a deeper understanding of sensor performance. Devices like Coriolis flowmeters – which, in addition to the standard physical quality testing, have passed a carefully chosen set of virtual tests – offer customers enhanced value through increased accuracy and robustness, as well as optimized material use.

In 2009 ABB began collaborating with the Dresden University of Technology to develop FE modeling techniques for electromagnetic sensors.

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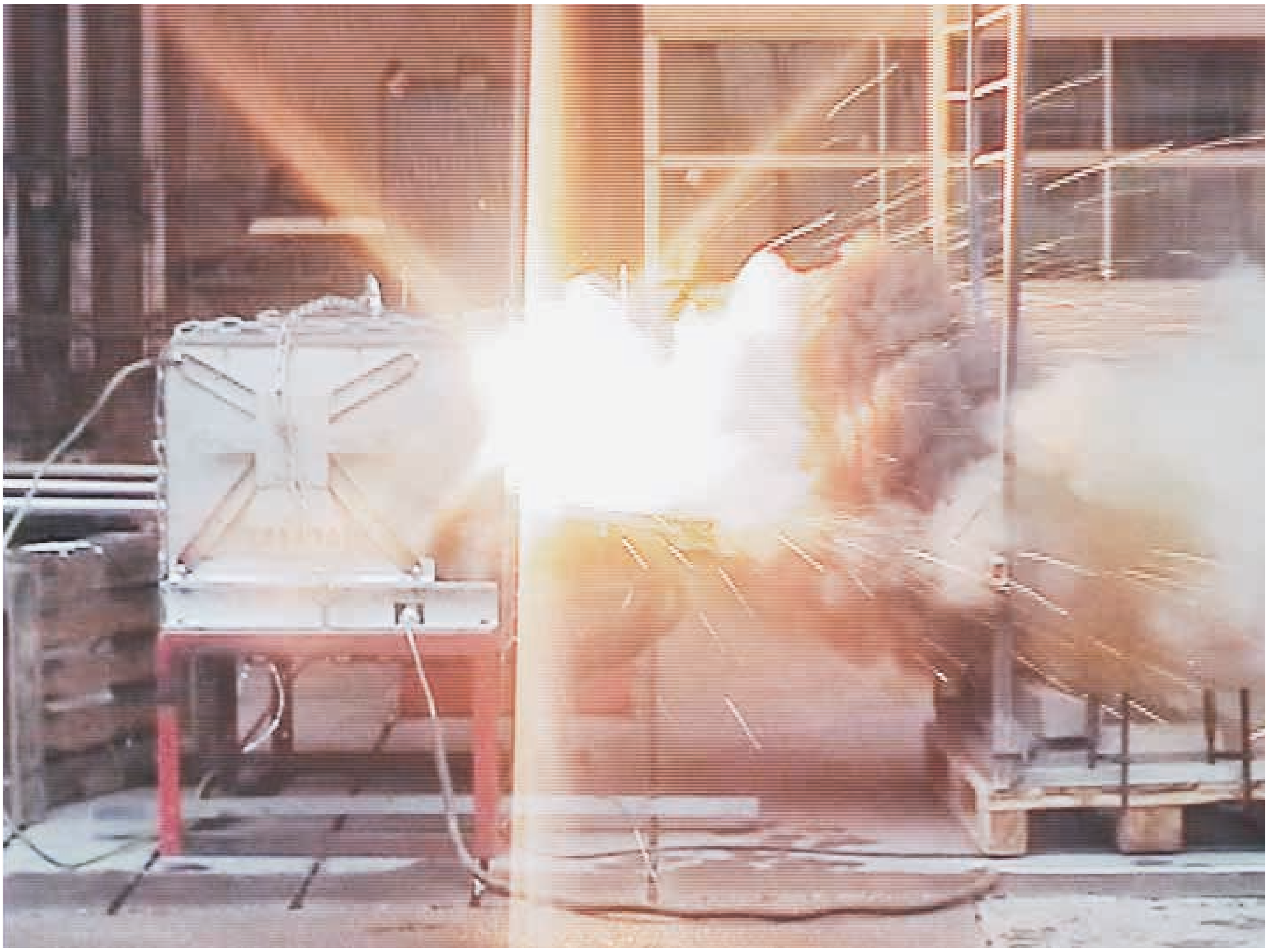
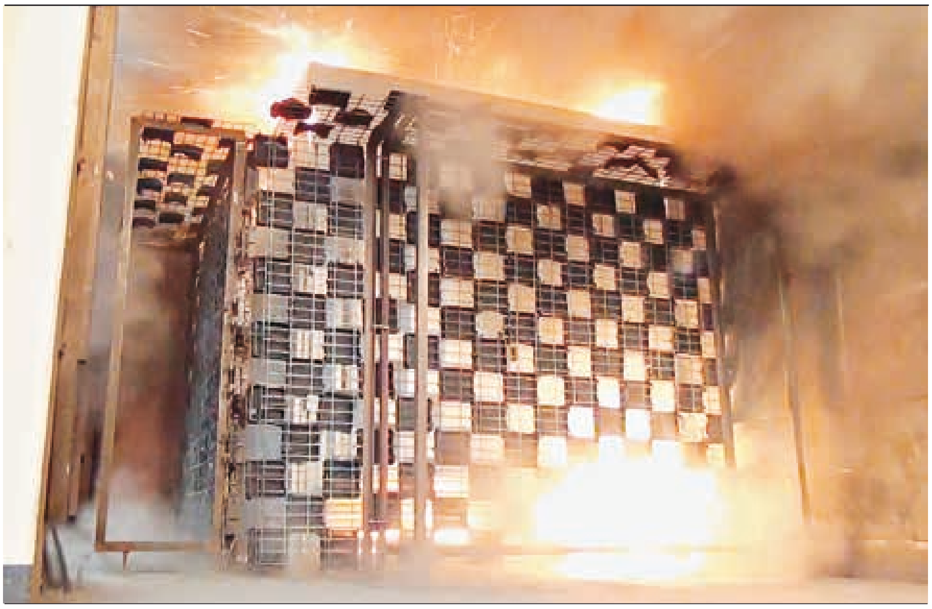


Feeling the pressure

Simulating pressure rise in switchgear installation rooms

EDGAR DULLNI, PAWEL WOJCIK, TOMASZ BLESZYNSKI – An internal arc fault is an unintentional discharge of electrical energy in switchgear. During the fault, short-circuit currents flow between phases and to ground. The arc heats the filling gas in the switchgear enclosure – either SF_6 or air, resulting in pressure rise. The incidence of a fault is very rare, but when it happens it may seriously damage the electrical equipment and the building and may even endanger personnel. It is only possible to evaluate the pressure rise in a building by calculation. Nevertheless, calculations should be substantiated by special tests allowing the measurement of external pressure rise. ABB has developed a calculation program that is easy to use by developers of switchgear and civil construction engineers.

1 Internal arc in switchgear during an arc fault test in the laboratory



Pressure rises stress switchgear enclosures mechanically. In order to avoid rupture, a relief device opens at defined pressure. The fault arc produces hot gas, which has to be directed in a controlled manner into the environment. Most often, exhaust channels are placed on top of the switchgear. These channels often possess a hatch or absorber at the end, where the hot gas is cooled down before it leaves the channel.

Standards eg, IEC 62271-200 [1] require switchgear to be safe for operating personnel, even if an internal arc occurs ➔ 1. Type tests not only verify that the switchgear enclosure withstands the pressure, but also prove that hot gases are directed away from personnel. IEC 61936-1 [2] requires that the building design shall take into account the pressure rise due to these exhaust gases. Switchgear arc fault tests do not cover this aspect, since the installation room is simulated by two perpendicular walls and ceiling, which do not present a gas-tight room allowing room pressure measurement. Therefore it is only possible to evaluate the pressure rise in a building by calculation. Another application for the calculation program is to simulate the pressure rise for different filling gases, ie, SF_6 and air. For validation, tests were conducted together with RWTH Aachen and TÜV Nord Systems GmbH.

Equations in the calculation program

Gas pressure in an enclosure depends on gas temperature, in accordance with the ideal gas law. Mass balance equations consider mass flow out of the enclosure. Compartments are represented by their effective volumes (components subtracted) and pressure relief areas in between. Gas properties such as the specific heat capacities are independent of temperature and uniform all over the volume [3].

Some fraction – called thermal transfer coefficient k_p – of the fault arc power heats up the gas in the arc compartment:

$$Q_1 = k_p \cdot W_{el}$$

The electrical arc power is evaluated from measured currents and phase-to-ground voltages:

$$W_{el} = (u_R \cdot i_R + u_s \cdot i_s + u_T \cdot i_T)\, t$$

The measured voltages are not necessarily identical to the arc voltage, because a three-phase arc can burn between two phase conductors, but also to the grounded enclosure. The pressure calculation tool either imports measured phase-to-ground voltages from a formatted data file or applies an empirical average phase-to-ground voltage.

All time-dependent quantities in the Internal Arc Tool (IAT) are regarded before and after a time step Δt. The following equation shows the mass flow out of the arc compartment into the exhaust compartment:

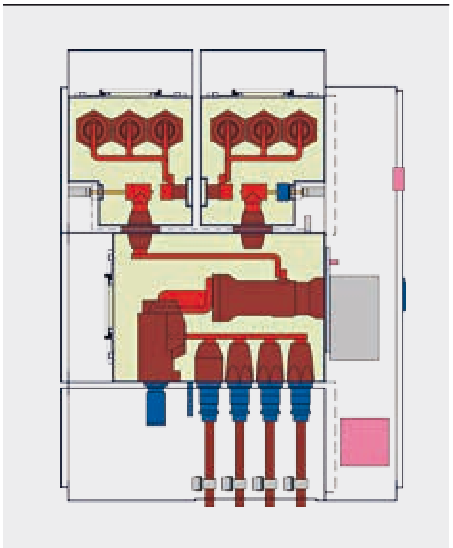
$$\Delta m_{12} = \alpha_{12} \cdot \rho_{12} \cdot w_{12} \cdot A_{12} \cdot \Delta t$$

α_{12} is the efficiency of a relief device with area A_{12} and considers the contraction of gas flow through an opening with sharp edges (0.7 to 1.0), but also the flow reduction due to eg, a mesh or absorber. When the relief device opens, the mass Δm_{12} escapes from the volume per time step. $\rho 12$ and $w12$ stand for gas density and gas velocity inside the opening according to Bernoulli's law [3]. This mathematical approach allows for the calculation of the pressure rise in all involved volumes.

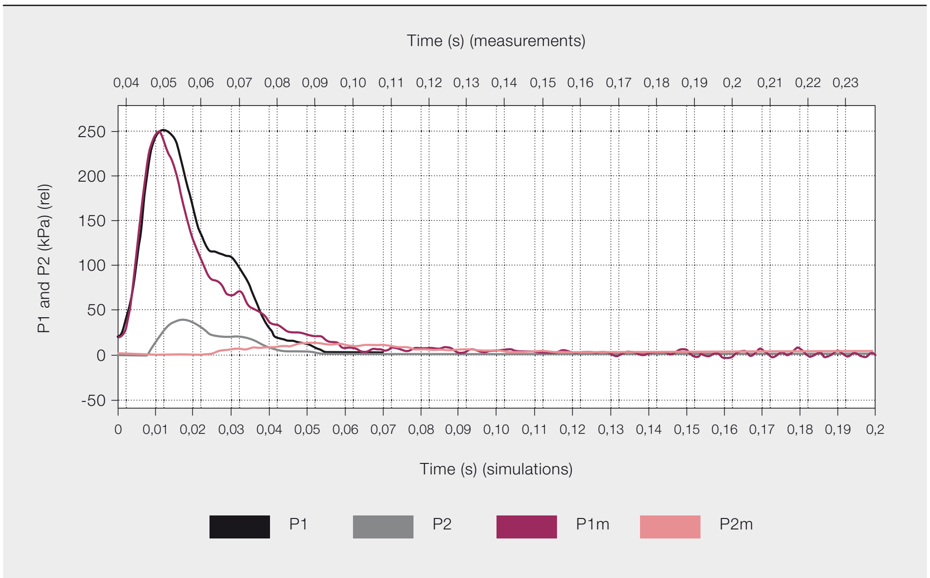
The accuracy of the calculation is limited by the applied simplifications. Because of the assumption of constant specific

Title picture
Image captured from a high speed video showing the controlled exhaust of hot gasses from medium voltage switchgear during an internal arc test. ABB software calculates the observed pressure development inside the switchgear and in the installation room.

2 Cross-section of ABB switchgear type ZX2 with arc initiated in busbar compartment and pressure relief into the channel on top

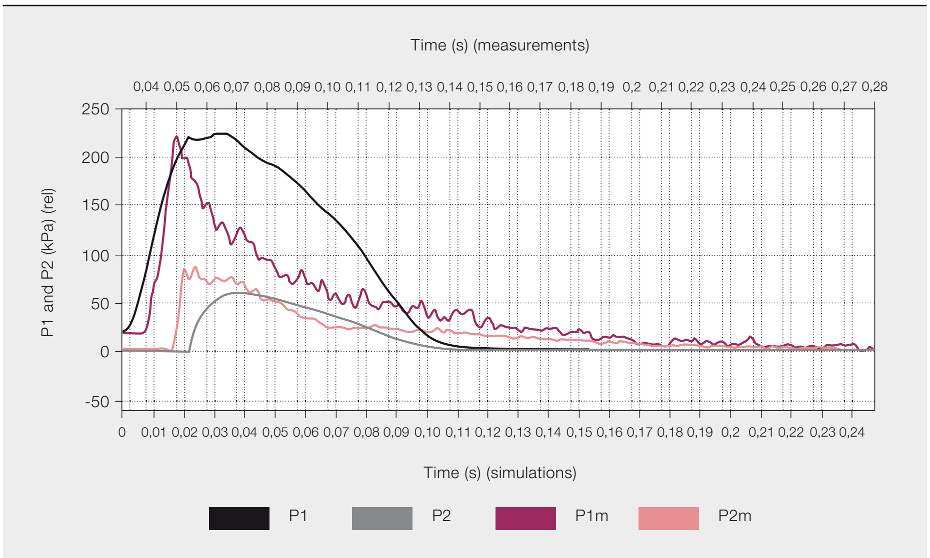


3 Comparison of calculated and measured pressure developments for an internal arc in ZX2 using air as filling gas (38 kA)



Type tests not only verify that the switchgear enclosure withstands the pressure, but also prove that hot gases are directed away from personnel.

4 Comparison of calculated and measured pressure developments for an internal arc in ZX2 using SF_6 as filling gas (35 kA)



heat capacities, dissociation of gas molecules into fragments is not considered. This starts at 6,000 K in air and 2,000 K in SF_6. However, agreement with test results is obtained also for higher gas temperatures.

If a considerable amount of gas flows out of the switchgear compartment, fewer and fewer gas molecules remain in it. If the heating fraction k_p of the arc energy stays constant in time, an ever increasing gas temperature would result, exceeding known arc temperatures of 20,000 K by far. This is not realistic and also generates numerical instabilities. To avoid this, the k_p is taken as density dependent [4]. This modification allows the extension of the calculation to longer fault durations and for calculating the pressure rise in the installation room.

Tool description

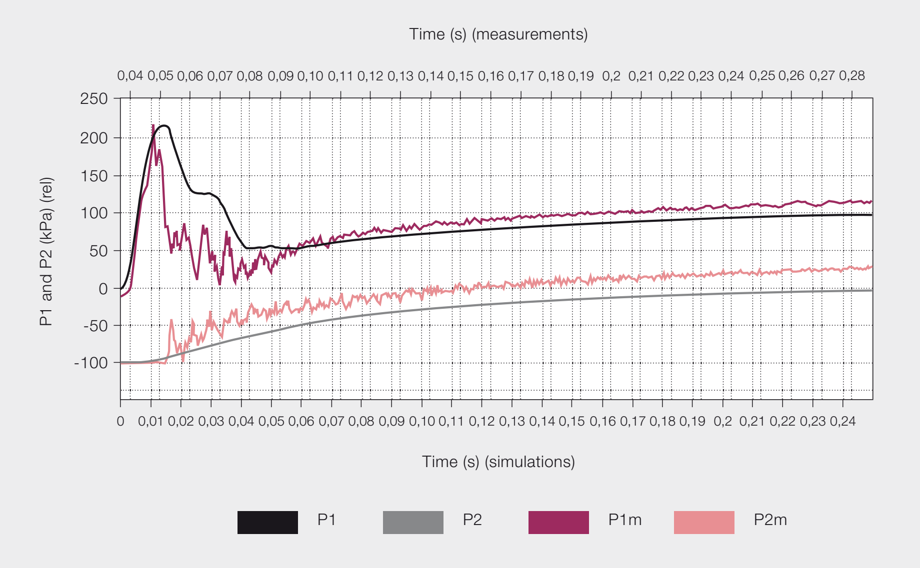
The proposed methodology was successfully implemented in the IAT simulation software at ABB's Simulation Tools Center (STC).[1]

The tool consists of two parts: graphical user interface (GUI) and solver. The solver was developed in Python and the user interface in Java. The main features delivered by the IAT GUI are:

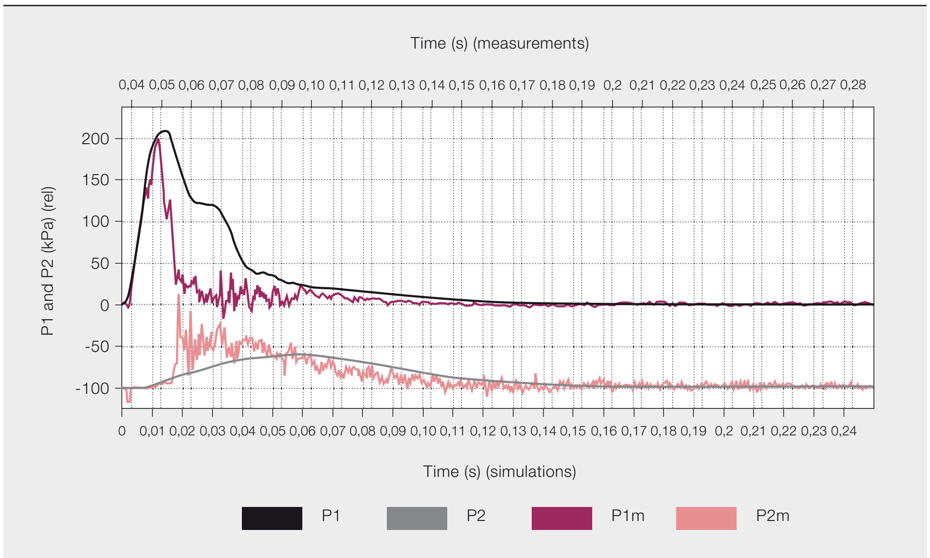
Footnote

1 See also ➔ 7 on page 71.

5 Comparison of calculated and measured pressure developments for an arc in a test arrangement using an 8 m³ closed container (20 kA)



6 Pressure developments as in ➔ 5 with 0.3 m² relief opening (20 kA)



Simulation time takes less than 10 s for a maximum arc duration of 1 s on a laptop.

1) Set up model parameters
2) Run solver
3) Visualize results
4) Create report

Model parameters can be set directly or can be selected from a drop-down list and each parameter is validated. When the model is ready, the user is able to start the simulation. They are guided through the simulation setup by a simple wizard. Simulation time takes less than 10 s for a maximum arc duration of 1 s on a laptop. The calculations are performed with a constant simulation time step of 0.05 ms. For comparison with tests, measurement data in proper format can be imported.

The following characteristics are drawn:
1) Pressures vs. time
2) Phase currents vs. time
3) Phase to ground voltages vs. time
4) Integrated arc power vs. time

Plots can be dynamically modified and no additional editor for visualization is needed. Examples are shown in ➔ 3 – 9.

Additionally, text files with simulation parameters (selected input and output values) and result data are generated.

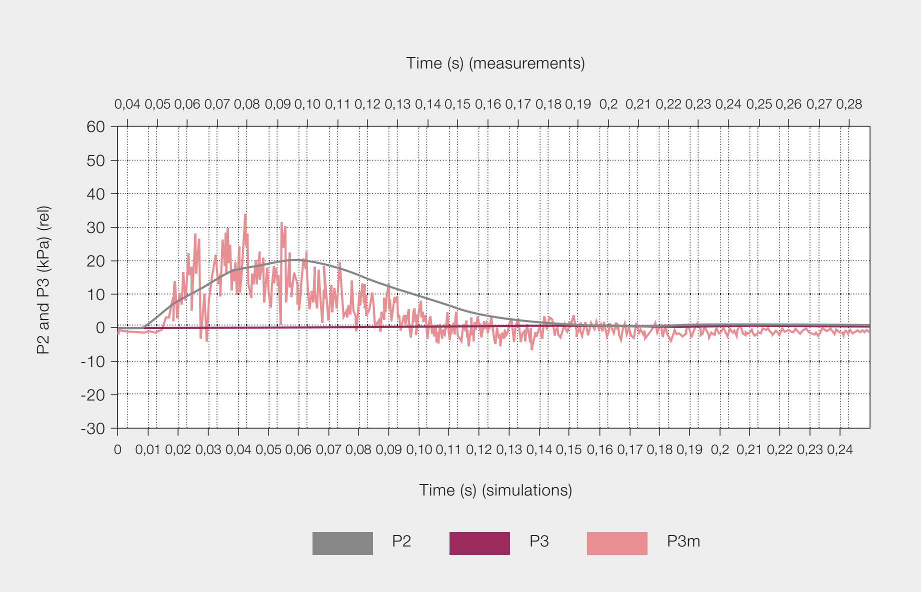
Comparison of results

The IAT results were compared with results from tests obtained with ABB switchgear and specially designed experiments.

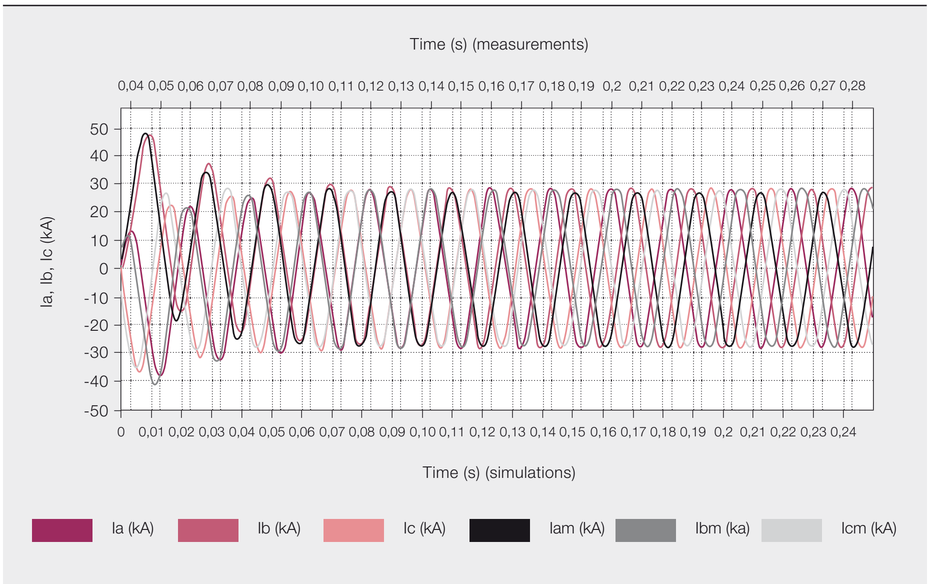
The first comparison relates to gas-insulated switchgear (GIS) where the insulating gas SF_6 could be replaced by air. The cross-section of the ABB switchgear ZX2, where the arc was ignited in the busbar compartment, is shown in ➔ 2. The pressure relief device was a thin burst disc with an area of 0.049 m² opening into the channel on top at an over-pressure of 220 kPa. The fault current had a value of 39 kA and was applied for 1 s. The oscillograms show the time development of the calculated pressure in the arc compartment (black in oscillograms) and exhaust channel (gray in oscillograms), and the measured data (purple for the former, pink for the latter) up to 250 ms after arc ignition.

The exhaust of hot gas and subsequent pressure rise in a closed installation room were investigated in a special experiment.

7 Pressure in the container measured at another location than for ➔ 6



8 Measured and applied phase currents showing the initial asymmetry



In ➔ 3, measurement and calculation of pressure rise, peak and drop in the arc compartment filled with air are in good agreement. k_p is taken as 0.5 in accordance with published data, and arc voltage (phase-to-ground) of 300 V is taken from test. The calculation of pressure in the exhaust channel shows less satisfying correlation with the test results due to travel time effects of the exhausted gas, which cannot be implemented in the IAT.

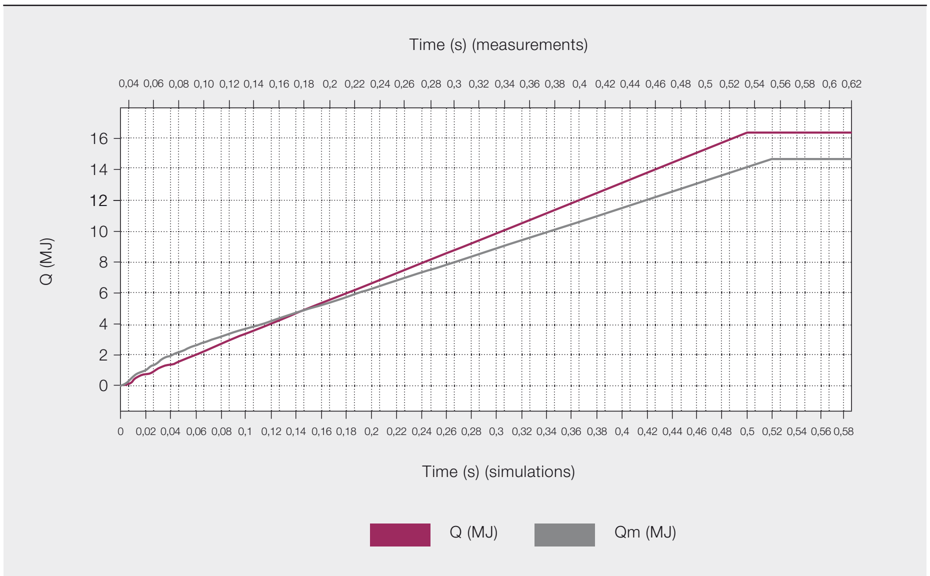
For the filling gas SF_6 ➔ 4, the reproduction of the peak pressure is again good, but the drop of pressure after the opening of the relief disc is less satisfying. The calculation provides a longer residence time of the gas than observed in the test. k_p is taken as 0.75 consistent with publications, and arc voltage is 400 V according to tests.

The tool can calculate pressure rise in installation rooms with relief openings provided by, eg, windows or hatches.

Many tests were recalculated. The inaccuracy in the peak pressure in the arc compartment is in the range of ±20 percent, mainly determined by the uncertainty of response pressure of the relief device. The drop of pressure after relief is simulated with an error of a factor of two. This is of no concern for the assessment of pressure withstand of the switchgear, since it is the peak pressure that is decisive.

The peak pressure in exhaust channels can also be calculated. However, the inaccuracy might be up to ±40 percent, which originates from the effects of pressure waves in elongated channels.

9 Arc energy determined from the multiplication of phase-to-ground voltages and currents (purple from IAT; gray from measurement)



The internal arc simulation tool is a useful element to improve design efficiencies and increase safety, especially when it is impossible or impractical to carry out real-world testing.

The exhaust of hot gas and subsequent pressure rise in a closed installation room were investigated in a special experiment [4]. The installation room was simulated by a gas-tight container of 8 m³. ➔ 5 shows pressures determined in test and calculations. The drop of pressure in the arc compartment, after response of the relief device, deviates from the measurement, but the saturation of the pressure rise in the container is simulated satisfactorily. This is due to the decrease of k_p implemented in the IAT in dependence of the decreasing gas density in the enclosed switchgear compartment. If the arc energy heats up the total container volume uniformly in time, as for a freely burning arc, the pressure would linearly rise to 345 kPa instead of the measured 154 and calculated 114 kPa.

The calculation tool implements the density dependence of k_p according to the following formula applied for $\rho(t) < \rho_c$:

$$k_p(t) = k_p \cdot c_0 \cdot (\rho(t)/\rho_0)^{0.5}$$

c_o is adapted to provide a continuous transition from the initial k_p. ρ_c is 1 percent of the normal gas density ρ_0 at 100 kPa for air and 20 percent for SF_6. Corresponding results were gained from the tests using SF_6 and air in a similar arrangement [4].

The tool can also calculate the pressure rise in installation rooms with relief openings provided by, eg, windows or hatches. ➔ 6 shows a test result using the same 8 m³ container with a relief area of 0.3 m². The actual geometry of the installation room and the position of the relief opening and sensors cannot be considered in the IAT and will give deviations to reality. An example is the higher initial pressure in ➔ 6 due to the direct stream of gas to the sensor. Another sensor positioned aside shows better agreement with the calculation ➔ 7. Only computational fluid dynamics (CFD) may provide better results.

Estimated pressure

Within reasonable limits both peak pressures in the switchgear compartments and exhaust volumes match each other in test and simulation results. Inaccuracies are caused by the simplifications introduced in the tool (eg, ideal gas assumption and generic outflow function). The IAT can be used for simulation of the pressure effects of fault arcs in switchgear. The uncertainty in the prediction of the peak pressure is in the range of ±20 percent concerning the arc compartment. A reliable arc voltage is required determined from tests on similar switchgear. The tool can also be used to estimate the pressure rise in an exhaust volume or installation room with or without relief openings considering proper safety margins. The internal arc simulation tool is a useful element to improve design efficiencies and increase safety, especially when it is impossible or impractical to carry out real-world testing.

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Robot design

Virtual prototyping and commissioning are enhancing robot manipulators and automation systems development

RAMON CASANELLES, XIAOLONG FENG, THOMAS REISINGER, DIEGO VILACOBA, DANIEL WÄPPLING, PETER WEBER –
Industrial product and application design continues to be an art where teams of engineers bring together their knowledge, experience and creativity to create something new. What has changed is how the created solutions or approaches are evaluated and assessed to make sure they lead to a better product. Instead of the simple trial and error efforts of the past, ABB uses sophisticated virtual prototyping and virtual commissioning methods to develop robot manipulators and automation systems that meet increasing performance requirements. Virtual prototyping facilitates the product design phase, and also improves the detailed engineering and function testing of a system. With regards to application testing, virtual commissioning is used to verify the functionality of an automation system before real commissioning starts. ABB's RobotStudio successfully reduces commissioning time by providing a virtual commissioning tool that enables realistic system simulations.

Title picture
Robots such as this ABB IRB 7600FX in the VOLVO Olofström press-shop in Sweden rely on simulation to meet increasingly demanding and complex requirements.

Robot manipulators face increasingly demanding and complex requirements, as do the automation systems using them. Machine builders and system integrators are now expected to deliver and commission systems with higher up-times in a shorter time period, with improvements in quality, performance and cost.

But ABB is able to meet this challenge, and the reason is twofold. ABB engineers take a mechatronic approach – considering mechanical, electrical, and software engineering simultaneously. And they use the latest simulation technology available, including dynamic simulations, 3-D CAD, finite element analysis, probabilistic design and optimization.

Virtual design – product development

An industrial robot is a mechatronic system with a mechanical structure, normally referred to as a robot manipulator, and a controller. A robot manipulator consists of structural links, speed-reducing gearboxes, servo motors, and brakes. Depending on the program for the specific application, the industrial robot performs its motion trajectory and fulfills the task in an automation system. The robot controller consists of a main controller for trajectory planning and servo drives controlling the electrical motors.

Designing an industrial robot manipulator is a complex engineering process. The major steps in this iterative process are:

- Kinematics design: deciding the number of joints, arm lengths and configuration
- Rigid-body dynamics design: designing the structure as well as accompanying motors, brakes, and gears (including motion control configuration parameters) that fulfill cycle-time and lifetime requirements
- Thermal design: assessing motor winding and motor shaft temperature based on thermal design criteria
- Stiffness design: assessing robot control performance based on eigenfrequency analysis or path accuracy analysis

Virtual prototyping is used to accurately assess the design of the robot manipulator by taking multiple parameters into account at the same time. These simulations are used to determine all the exact specifications for the robot design, such as weight, robot speed and acceleration, and robot accuracy.

> Virtual prototyping is used to accurately assess the design of the robot manipulators by taking multiple parameters into account at the same time.

For example, in optimizing the cycle-time of a press-tending robot loading and unloading dies in a press shop the challenge is to determine the correct specifications for gearboxes and select the drive-train control parameters that will minimize cycle-time and gearbox torque. With virtual prototyping, engineers take a

1 High-performance Twin Robot Xbar – TRX for press automation

Through virtual commissioning system tests can be conducted seamlessly and efficiently.

multi-objective optimization approach to analyze the best trade-off relationship between robot cycle-time performance and gearbox torque. Virtual prototyping allows the engineers to run thousands of tests to determine the best trade-off relationship for maximum performance with minimum torque.

Through these techniques ABB developed a twin robot solution that is used in innovative press automation applications, referred to as Twin Robot Xbar – TRX[1] → 1. The trade-off relationship between the press-tending performance and the total rated torque of the gearboxes was obtained with multi-objective optimization → 2. This relationship gives quantitative insight into the impact of robot performance on drive-train design and cost. For example, examination of two extreme design points at the Pareto front discloses that an increase in press-tending performance of 5 percent is achieved by increasing the drive-train cost by 7 percent.

A virtual controller emulates exactly the behavior of a real controller but runs on a standard PC.

System engineering

Once a successful industrial robot design is achieved, the next step is to successfully place the robot in an automation system. Together with devices like programmable logic controllers (PLCs), servo motors and drives, and the required mechanical equipment and software, the robot becomes part of a discrete automation system.

Virtual prototyping [1], [2] also significantly improves the detailed engineering and function testing of a system. Before the detailed work on the automation system can start, a conceptual design is created. The mechanical, electrical and software engineering groups then join the process. A three-dimensional layout created by the mechanical engineers becomes a virtual prototype for the robot engineers. By using RobotStudio, ABB's offline programming and simulation tool for robot applications, engineers can position virtual robots in the model, teach robot targets and paths, and check the robot's reachability. Programming and debugging of the robot applications can be done in the same environment and immediately applied to the virtual prototype by using virtual robot controllers, thus enabling short development and verification cycles. If remodeling is needed, as for example identified by reachability analysis, the required modifications can easily be communicated back to the mechanical engineers.

Using virtual prototypes in the detailed engineering phase does not have to be limited to robot applications. The simulations can be expanded to a much wider range of applications, as for example in developing complex PLC or motion applications, with significant advantages in development and testing.

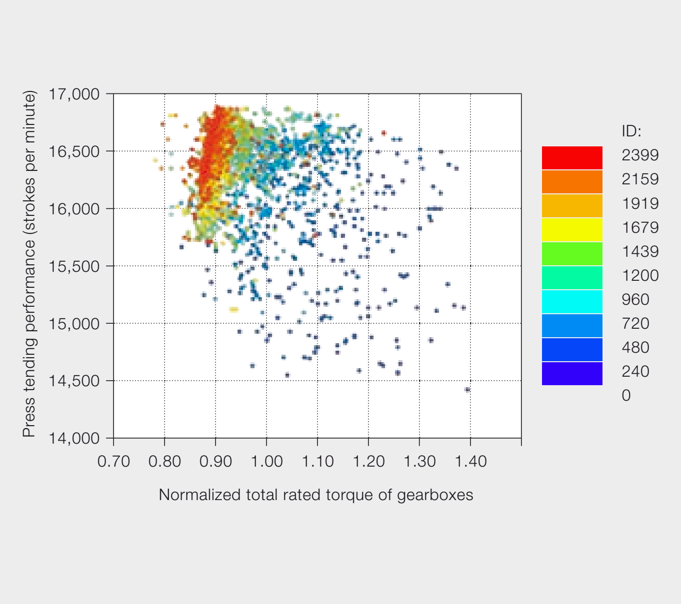
Virtual commissioning

Virtual commissioning is a simulation method for verifying the functionality of an automation system before real commissioning starts. The process involves replicating the behavior of hardware within a software environment, enabling a seamless transition from the virtual to the physical environment.

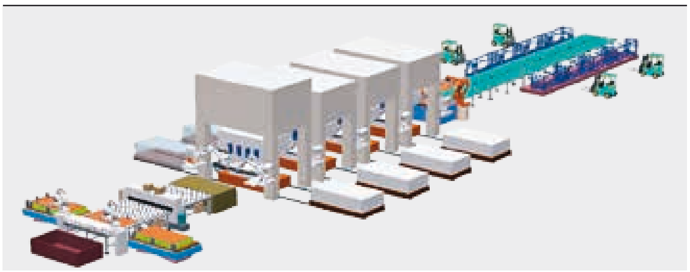
Footnote

1 TRX robot consists of two (4-axis) manipulators interconnected with a crossbar.

2 Internal design of Twin Robot Xbar – TRX robots created with multi-objective drive-train optimization



3 View of a virtual press shop created with ABB's RobotStudio



4 View on the virtual press shop model

During testing and implementation, virtual commissioning methods, like hardware-in-the-loop (H-I-L) and software-in-the-loop (S-I-L), are used for the integration and system tests up to the final acceptance test.

The process enables a seamless transition from the virtual to the physical environment.

Depending on which phase is being tested the applied virtual commissioning architecture adapts to the appropriate engineering stage of the process. In early test phases an S-I-L approach is used while in later test phases an H-I-L approach is better suited. S-I-L implies using virtual controllers. H-I-L means the real controllers executing the automation application to be verified are included in the test environment. A virtual controller emulates exactly the behavior of a real controller but runs on a standard PC.

Today H-I-L is the prevailing test scenario, which connects a dedicated PLC via fieldbus to a PC running a simulation model of the system. This architecture permits real-time execution of the control applications. Today's complexity of systems usually requires multiple interconnected controllers of different types to perform the automation tasks. Hence, simulating larger parts or a complete system requires a hardware infrastructure that is only available in later project phases.

To facilitate efficient testing in the early project phases – ideally concurrently to the application development – it is important to have an easy means of loading and sending the programs to the virtual test environment running on the same PC where the applications are developed. Detecting problems as early as possible, and being able to fix them with moderate effort, becomes increasingly important, especially since the software component of an automation system has dramatically enlarged over time and is increasing further.

To simulate the physical/target system or machine a virtual model of the system is needed; sensors and actuators need to be modeled. ABB's RobotStudio has smart components which mimic the behavior of real sensors and actuators and provide a process signal interface to connect them with real or virtual controllers thus enabling a comprehensive simulation of a system. Smart components can be used to flexibly integrate the functionality of various automation components in the virtual commissioning environment.

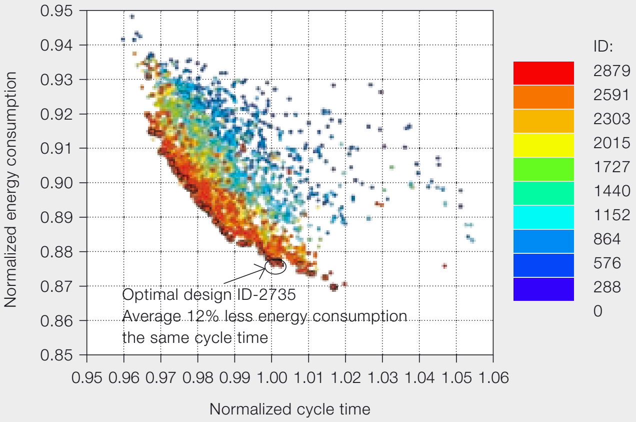
Tandem press lines

Press automation in an automotive press shop demonstrates the value of virtual commissioning technology. The size and power of presses that constitute a press line make doing real system tests on the test floor impossible. However, through virtual commissioning system tests can be conducted seamlessly and efficiently.

A tandem press line creates shaped plates that will later be welded together to constitute a car body. It consists of several aligned presses allowing the blanks passing through to get converted in shaped plates. The first press (draw press) performs the shaping and the others cut the inner and outer contours.

Due to the high cost of a tandem press line in the complete automation system, getting the maximum productivity is crucial to optimize the return on investment of such equipment. To achieve the best output rate the automation of transferring the plates between the different presses requires an optimum coordination between robots and presses.

To build the simulation model all elements/devices that constitute the system are introduced into ABB's RobotStudio → 3. The devices are simulated by smart components, including all logics, kinematics and dynamics properties that will make the model behave exactly as it would on a real site. Typical devices to be simulated are:



Energy-efficient design is a requirement rapidly gaining importance and one that can be evaluated using virtual prototyping. The objective is to select the drive-train control parameters, eg, allowable torques, and speed, that will minimize energy consumption at the same time that the cycle-time is minimized [3]. The problem is formulated into a multi-objective optimization problem with the drive-train control parameters as design variables and the following two conflicting objectives:

– Minimize energy consumption
– Minimize cycle-time

The Pareto front method for multi-objective optimization is used in this analysis. In the Pareto front optimization, two separate objective functions (cycle-time and energy consumption) are minimized during optimization. A set of Pareto optimal solutions, which explore the trade-off relationship between the two conflicting objectives, is obtained. The optimization algorithm MOGA-II [4] implements non-gradient methods especially suitable for this type of problem and is used for the energy-efficient design.

The optimization itself is an iterative process. The design variables, in this case the drive-train control parameters, are modified and ABB robot motion simulation software is run using the new set of variables to compute the energy consumption. Simulation results are used for computing both objective function and constraints values. This optimization loop is terminated when the limit for the maximum number of function evaluations defined for the MOGA optimization is reached.

Otherwise, the optimizer analyzes the objective function and constraint values and proposes a new trial set of design variable values. The optimization loop continues until the convergence criterion is met.

The illustration above demonstrates the solution space and the Pareto Frontier of such a multi-objective optimization showing the trade-off relationship of the cycle time performance and the energy consumption. The selected design from the optimal Pareto Frontier shows about a 10 percent improvement of the energy consumption without scarification of the performance of the industrial robot under optimization.

– Presses with dimensions, control, I/O signals, motion curves
– Robots and other automation devices
– Other mechanical components like destacking tables, blank washer, conveyors and safety elements

These components can be taken from libraries, if they are already in, or added from other sources or even created according to customer specifications.

Once virtually configured, the environment is ready for realistic system simulations. Different scenarios, corresponding to real production cases, can be simulated. ➔ 4 shows a detailed view of the virtual press shop model with the programmed robot motion path highlighted. The optimization of the line performance might require reprogramming of robots, press motion and logics, or adaptations of parameters previously generated. Knowing the performance prior to the real installation is extremely valuable considering the costly risk of not obtaining the expected performance in the real system.

The use of the virtual simulations is not limited to design and commissioning ➔ 5: The introduction of new production processes can be prepared much more easily and diagnosis of eventual faults or potential production improvements can be analyzed prior to their implementation in the real system.

The virtual prototypes developed during the product design process and automation system engineering can also be utilized to support predictive maintenance, identify what components to exchange, and in some cases to optimize robot programs with respect to wear, cycle-time or energy consumption.

Additionally, the virtual prototypes can be run in parallel to the actual automation system in order to test optimized equipment or programs virtually before they are deployed on the real system.

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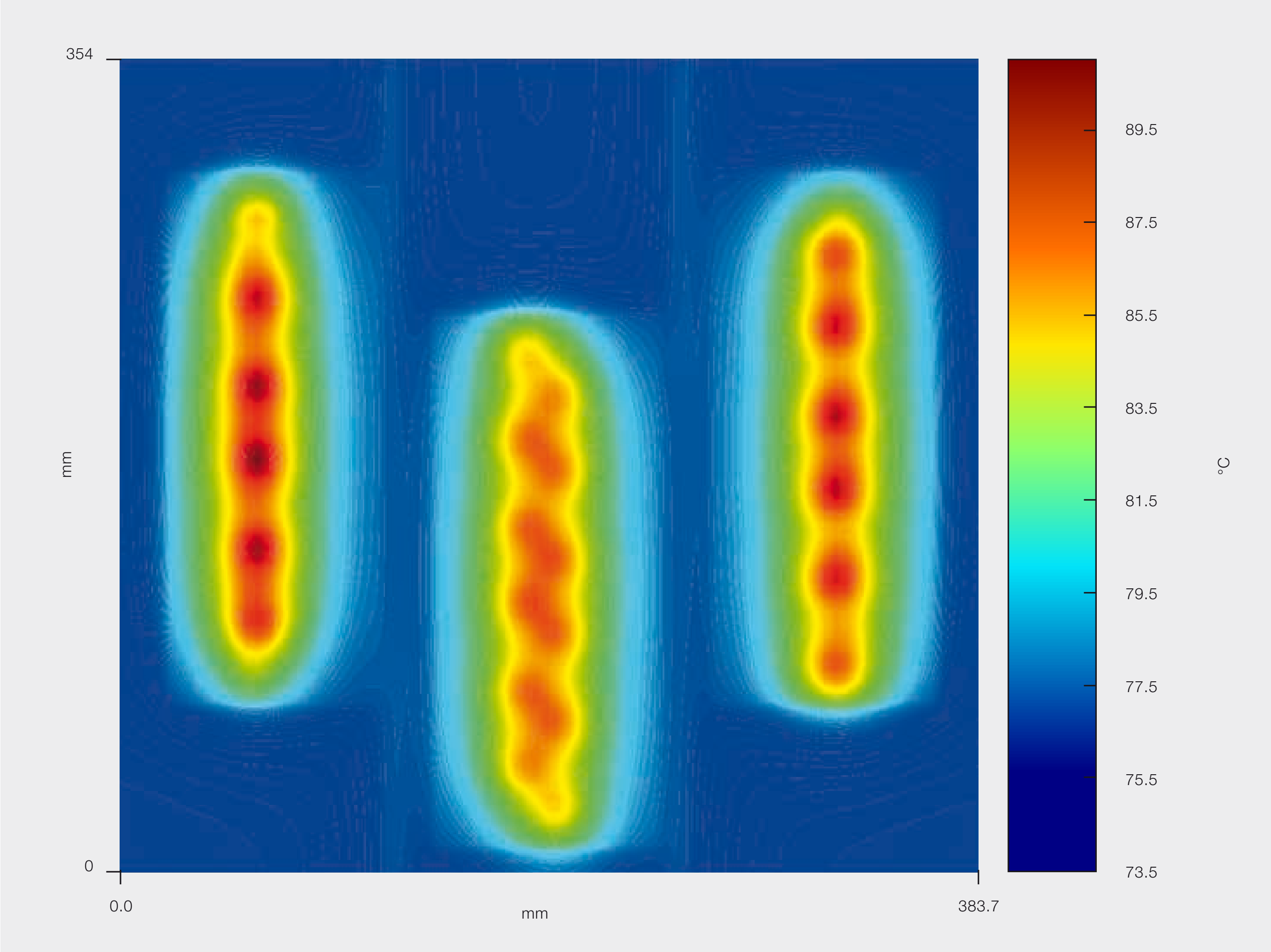


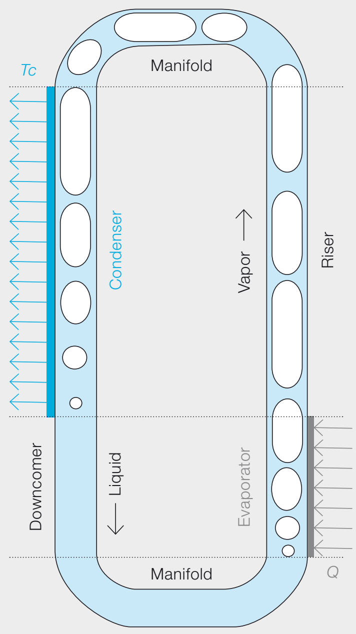
Integrated ingenuity

New simulation algorithms for cost-effective design of highly integrated and reliable power electronic frequency converters

DIDIER COTTET, BRUNO AGOSTINI, STANISLAV SKIBIN, GERNOT RIEDEL, PAWEL WOJCIK – Many readers may perceive power electronics engineering to be chiefly about circuit topologies and algorithms. Whereas these aspects continue to be vital, designers are increasingly also addressing challenges in other areas. The growing significance of integration has raised the profile of domains such as cooling, interconnects and voltage insulation and is bringing about improvements in power density, electromagnetic compatibility (EMC), and reliability. With the rising complexity of these technologies, optimal designs are no longer possible without recourse to state-of-the-art simulations.

Newly developed semiconductor devices permit faster switching at lower losses and operation at higher temperatures, while also raising fresh challenges in terms of integration.

1 Two-phase thermosyphon principle



$$\frac{dp}{dT} = \frac{L}{T\,(\Delta V)}$$

Power electronics is one of the principle enabling technologies in domains such as renewable power generation, efficient power usage in industrial automation, control of power flow in smart grids, and low-loss power transmission and distribution using DC technologies. The relevant performance measures for converters in these applications are conversion efficiency, control dynamics, reliability (or availability), power density and cost.

Differentiating aspects with regard to converter design lie in the choice of integration technologies, for example enclosure materials, cooling methods, interconnections and electrical insulation. The design challenges in integration are:
– Thermal losses
– High-current conduction
– High-voltage insulation
– Electromagnetic noise
– Electro-thermo-mechanical stress

Simulations are now a state-of-the-art component of development processes in these domains. Three-dimensional (3-D) finite element analysis (FEA) of power semiconductors helps optimize the manufacturing processes and switching characteristics. At system-level, the current control schemes and the process control algorithms are simulated using circuit simulators, often combined with multi-objective optimization methods.

Recent years have seen significant advances in the domain of wide band gap (WBG) power semiconductors, bringing first silicon-carbide (SiC) and then gallium-nitride (GaN) devices to the market. These new devices permit faster switching at lower losses and operation at higher temperatures. While this delivers many benefits in terms of energy efficiency, power density and new applications, it also raises fresh challenges in terms of integration. This article looks at three integration areas where new simulation methodologies had to be developed:
– Two-phase cooling for high power density and high reliability
– Design for electromagnetic compatibility (EMC)
– Electro-thermal simulations for reliability and lifetime prediction

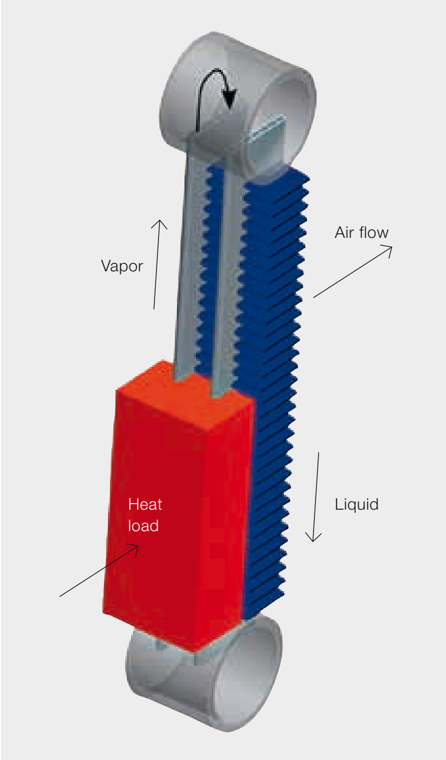
Cooling

Air and water are commonly used for cooling in electronics and accurate simulation tools are available for both (eg, ICEPAK, QFIN).

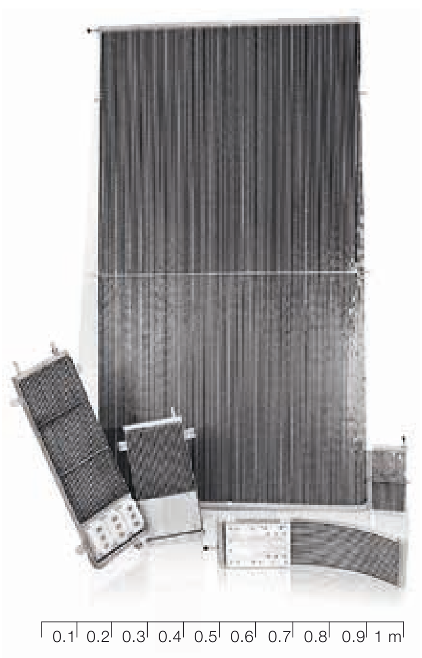
In power electronics, two-phase cooling thermosyphons are a particularly interesting alternative to active cooling meth-

Title picture
Result of COTHEX baseplate temperature distribution simulation

2 COTHEX technology principle



3 COTHEX family (base to air and air to air)



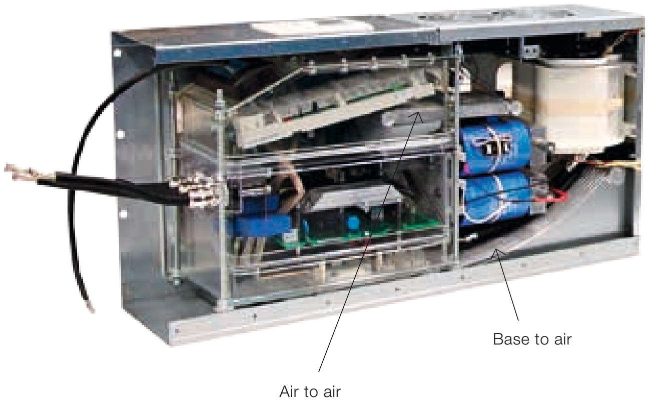
The compact designs adopted to obtain high power densities also increase electromagnetic coupling between different parts of the equipment.

ods [1]. In a thermosyphon, fluid circulates by gravity because of the density difference between the liquid and the vapor ➔ 1. Thus, the use of dielectric fluids and pumpless operation with high boiling-heat transfer coefficients is an attractive combination for the cooling of devices with higher power densities. The method displays higher reliability than pumped water (no moving parts or electrical insulation issues). ABB has developed a compact thermosyphon heat exchanger based on automotive technology. It uses numerous multiport extruded tubes with capillary sized channels arranged in parallel and brazed to a heated baseplate in order to achieve the desired compactness ➔ 2–3. The technology calls for new modeling methods, however, as it can presently not be adequately covered using commercial tools. Simulations of two-phase thermosyphons should predict the thermal resistance from heat source to heat sink (eg, ambient air), but also critical parameters such as dry-out (to ensure temperature uniformity), critical heat flux (to avoid temperature runaway), pressure losses or optimal fluid filling. ABB's two-phase thermosyphon model is based on the solving of the mass, momentum and energy two-phase conservation equations. Suitable correlations and models from literature or from university collaborations are used to calculate the pressure drop, void fraction and heat transfer coefficient in the successive sections of the thermosyphon.

Two-phase cooling thermosyphons are a particularly interesting alternative to active cooling methods.

The residuals of these conservation equations are then evaluated and minimized with a suitable minimization algorithm (SIMPLEX). This two-phase flow model is coupled to a finite volume partial differential equation (PDE) solver to determine the heat spreading through the baseplate ➔ title picture. Since there is no pump to drive the fluid inside a thermosyphon, the fluid flow rate and therefore the cooling performances are very sensitive to many parameters such as tube lengths and diameters, heat flux distribution, fluid pressure and the nature and amount of fluid. These simulations

4 Low-voltage drive with one base-to-air and one air-to-air COTHEX installed



For many components accurate high-frequency modeling methods had to be developed specifically.

thus allow the optimal product design to be built while bypassing a considerable amount of prototyping effort ➔ 4.

EMC

Modern power-electronic converters are complex devices in which high currents and voltages coexist with disturbance-sensitive control and communication signals. The compact designs adopted to obtain high power densities also increase electromagnetic (EM) coupling between different parts of the equipment. To provide reliable and safe operation of converters, the electromagnetic compatibility (EMC) of the device must be ensured. Three aspects of EMC have to be taken into account:

- Ability of the device to work in a certain EM environment (immunity)
- Emitted EM noise toward the environment must be kept below certain limits (emission)
- EM interference between different parts of the same device (EMI)

The first two items are a subject of regulations in the form of specific emission and immunity norms. The third item defines internal robustness and reliability of a device.

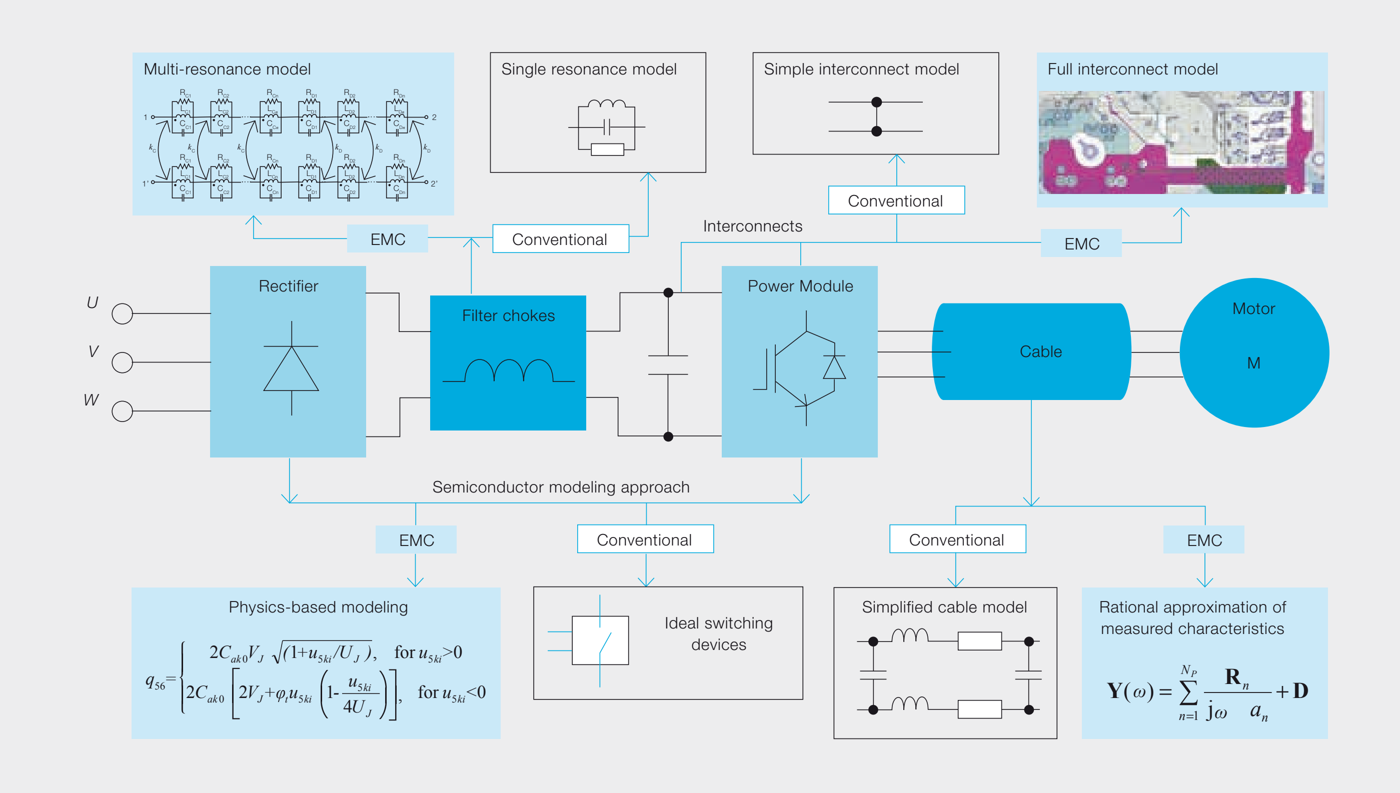
The trends toward compact design, high power density and fast-switching power semiconductors are making the EMC design of power-electronic equipment increasingly challenging. Too often, trial and error is the main approach when it comes to dealing with EMC in power-electronic devices. In such scenarios, measurements are performed on completed prototypes in which layouts and components are already fixed. Modifications are difficult at this stage and typically lead to delays.

In contrast, a smarter EMC design approach starts with system level EM simulations. The advantages of this method are:

- EM effects in the converter and its components can be taken into account at an early design stage.
- HF simulations of the complete converter can help understand and prevent possible EM disturbances.
- Based on EM simulations, optimal filter and layout designs can be achieved using numerical optimization algorithms.

The advantages of the simulation method may seem obvious, but the preparation of adequate converter models is a complex procedure. In order to be able to obtain usable simulation results, both discrete components (eg, capacitors and semiconductors) and mechanical and interconnect structures (eg, heat sinks, PCBs, cables) must be modeled precisely. The overall number of components in the system-level circuit model can easily exceed 100,000.

The different component and interconnect types existing in a converter demand different modeling methods and tools ➔ 5. For some of the components (PCBs, heatsink, capacitors), commercial tools are available. However, for



Power converters operating in remote or difficult-to-reach areas are required to continue functioning for decades.

many other components (eg, long three-phase power cables, common mode chokes) accurate high-frequency modeling methods had to be developed specifically [2, 3]. Thus EMC simulations for power electronics applications is growing to a more complex EMC simulation framework. This includes development and implementation of new component modeling techniques and tools (in collaboration with STC → 7), and the know-how surrounding selection and combination of component models into a system-level model, as well as post-processing and analysis of the simulated quantities.

Reliability

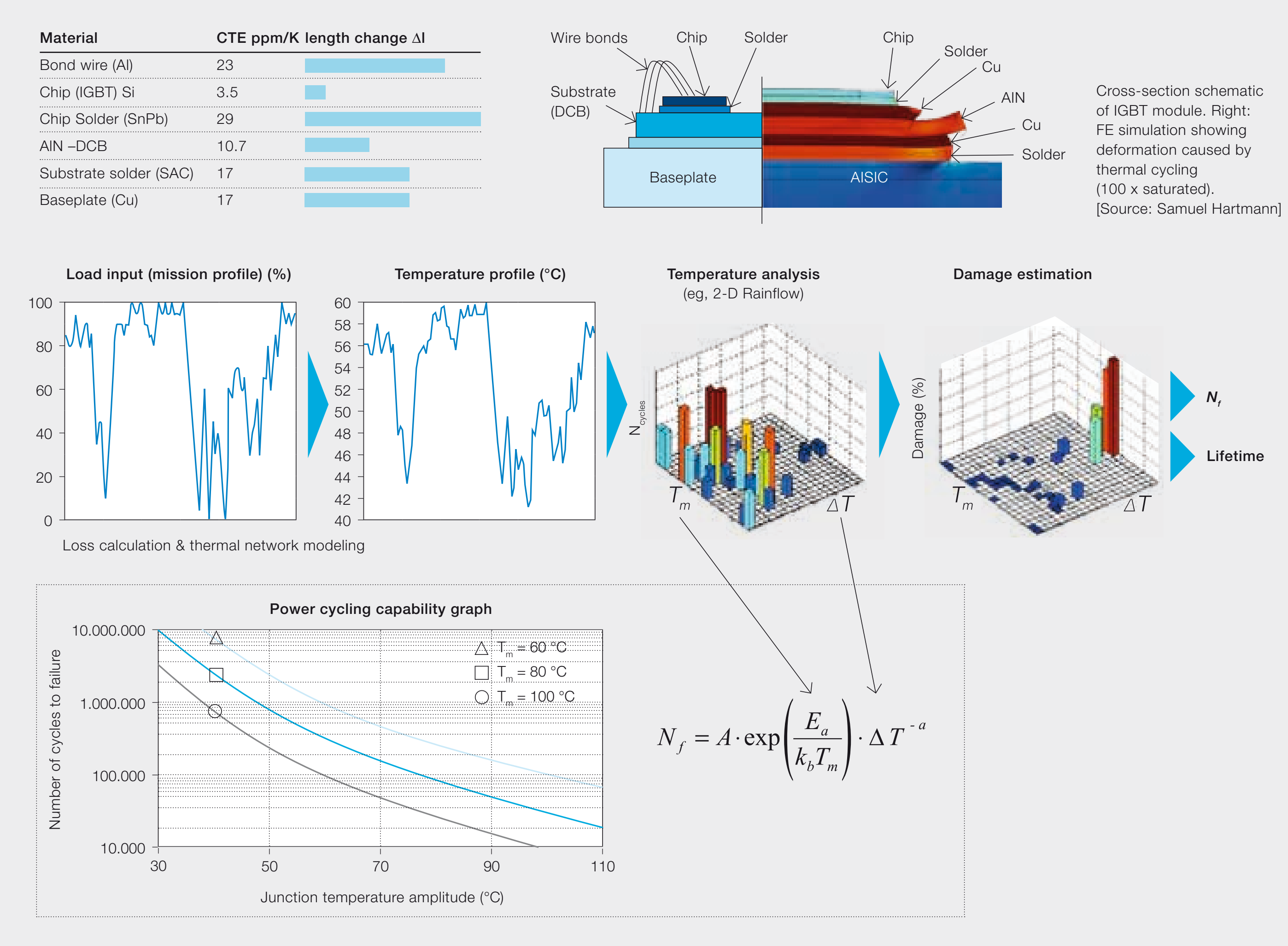
Power converters operating in remote or difficult-to-reach areas (such as offshore wind power installations) are required to continue functioning for decades. The location-specific challenges of maintenance and service interventions raise the importance of reliability.

In general, it can be said that a system's reliability is the product of the reliability of its parts. Each part can fail, either due to wear or due to excessive stress, and in doing so can engender system malfunctions. The more the individual parts are stressed, the higher the likelihood of a failure. Stresses can include (but are not limited to) applied electric fields, humidity and temperature.

The heart of every power electronics system is its array of semiconductor switches. Typically they are packaged in power modules providing insulation, internal current distribution and protection. These modules are made of different materials, each with its own coefficient of thermal expansion (CTE) → 6. When subjected to temperature changes (eg, due to load changes) this mismatch in CTE values causes mechanical stress – and ultimately wear – at the interfaces, which can ultimately break. For example, one cause of failure in IGBT (insulated-gate bipolar transistor) modules is the connection between the silicon chip and the attached aluminum bond wires breaking.

6 Lifetime modeling and simulation methodology

Material	CTE ppm/K	length change Δl
Bond wire (Al)	23	
Chip (IGBT) Si	3.5	
Chip Solder (SnPb)	29	
AlN –DCB	10.7	
Substrate solder (SAC)	17	
Baseplate (Cu)	17	



Cross-section schematic of IGBT module. Right: FE simulation showing deformation caused by thermal cycling (100 x saturated). [Source: Samuel Hartmann]

$$N_f = A \cdot \exp\left(\frac{E_a}{k_b T_m}\right) \cdot \Delta T^{-a}$$

Since this failure mode is well understood, manufacturers provide cycling capability graphs for their IGBT modules. These can be used as basis-of-lifetime simulations using the following steps.

- Definition of a possible load (mission) profile: What kind of stresses and environment will the components see in their lives?
- Loss calculation: Losses in the semiconductor switches are calculated from the load profile.
- Temperature profile calculation: In conjunction with thermal network models, transient temperature profiles are calculated for each semiconductor switch.
- Analysis of temperature profile: The temperature profile is analyzed according to the main stress parameters, ie, temperature swings, ΔT and median temperature T_m.
- Damage estimation: For each ΔT and the corresponding T_m the expected damage is calculated from cycling capability curves.
- Lifetime estimating: The lifetime of the semiconductor is given by the time needed to accumulative critical damage.

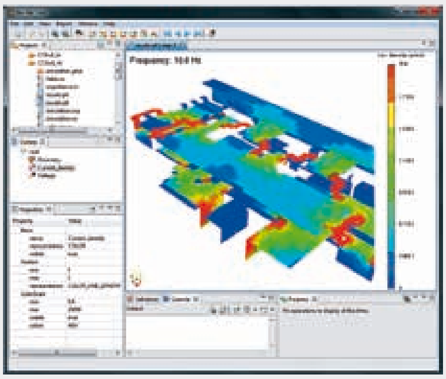
> The more the individual parts are stressed, the higher the likelihood of a failure. Stresses can include applied electric fields, humidity and temperature.

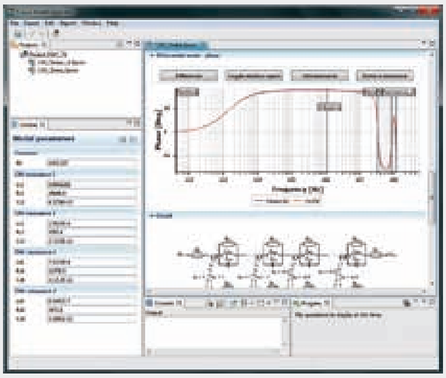
A similar procedure is applied for all other failure modes that may occur. In power modules for example, the solder joints suffer from thermo-mechanical cycling. In contrast to aluminum bond wires, the solder materials experience significant creep. Therefore finite element modeling or other numeric simulations are applied to calculate the damage induced by the applied load profile that finally determines the expected lifetime [4]. Of all the calculated failure modes, the shortest lifetime defines the lifetime of the component (in this case, the IGBT module) and thus the system in which it is used.

Outlook

Enabled by continuing improvements in computing technologies, the size and complexity of simulations will continue to grow. At the same time, advanced software interfacing and scripting tools will allow the coupling of further simulations in different fields. While bringing many advantages to product design and performance prediction, these developments will also lead to increased com-

7 Simulation Tools Center





ABB's Simulation Tools Center (STC) group was established in 2009 in Krakow, Poland. It provides professional power electronics simulation software for ABB. STC's services include:

- Development of dedicated and easy-to-use graphical user interfaces (GUI) for tools and algorithms developed in the frame of research projects in the various ABB corporate research centers.
- Programming of data interfaces between various internal or commercial simulation software to allow for coupled simulations.
- Long-term maintenance of the internally developed tools.
- User support, including tools training, typically teaming up with the scientists that developed the solvers.

The tools developed can, for instance, support design algorithms for new developed power electronics integration technologies (eg, new cooling devices). The availability of such tools significantly accelerates the transfer of new technologies from research into products.

Other tools provide new simulation methodologies and solvers, which are commercially not available. They therefore close important gaps in the simulation landscape, such as for example in the field of electromagnetic compatibility (EMC).

An important aspect of coupled simulations is that results from one simulation (or measurement) can be translated to input models for other tools. One such an example is the "busbar tool" (BBT) software, a dedicated tool for electromagnetic design of power interconnects (busbars). BBT not only provides the relevant impedances, current densities and field patterns, but also does post-processing of mechanical forces and exports busbar macro models for further simulations at circuit level (eg, in SPICE or MATLAB Simulink).

Another example is the "circuit model generator" (CMG) that creates high-frequency equivalent circuit models of inductors, common mode chokes and induction machines using measured or simulated impedances.

Finite element modeling or other numeric simulations are applied to calculate the damage induced by the applied load profile that finally determines the expected lifetime.

plexity in terms of handling the growing number of tools, models and results, and typically will also involve designers in different locations. It is therefore all the more crucial to focus on the necessary infrastructure and to provide long-term maintenance of the various commercial and self-developed tools and models. At ABB, this task is performed by the company's power electronics simulation tools center (STC) → 7.

As a result of the focused use of state-of-the-art simulations, integration technologies will keep pace with the increasing performance of semiconductor devices and their challenges. The future of power electronics applications will thus be characterized by continuous increase of power density, improvement of product reliability and reduction of cost per power.

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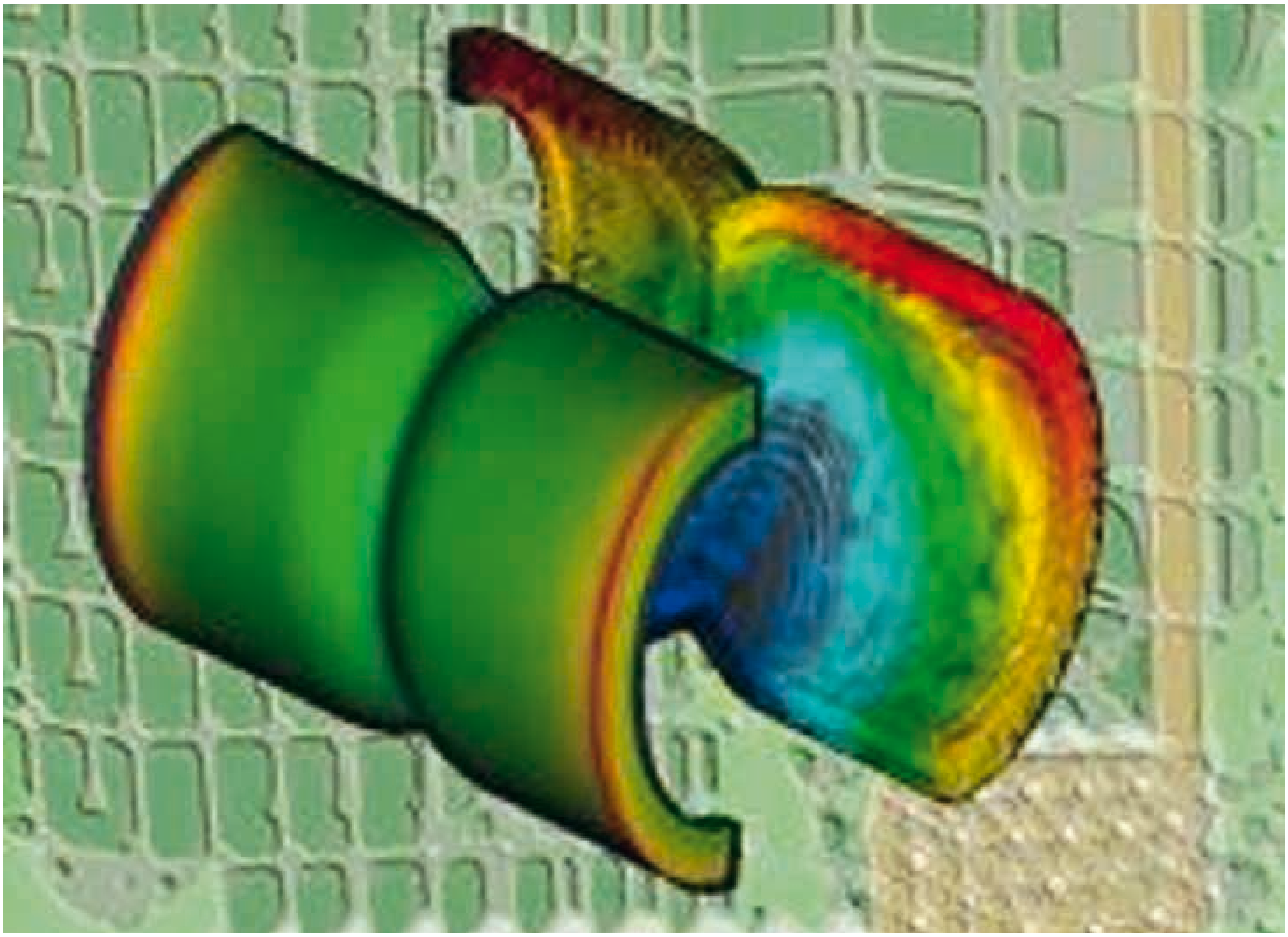


Molding the future

Polymers processing enhanced by advanced computer simulations

ROBERT SEKULA, KRZYSZTOF KASZA, LUKASZ MATYSIAK, LUKASZ MALINOWSKI, DARIUSZ BEDNAROWSKI, MICHAL MLOT, GERHARD SALGE
– Due to their excellent electrical, thermal and mechanical properties, polymeric materials are the principal insulating materials used in many ABB power products. Because of the shape complexity and wide range of parameters used in manufacturing technologies, there can be product quality challenges. For example, air voids, incomplete filling, premature gelation, incorrect curing propagation, local overheating, cracks and deformations may appear in the insulation. However, through advanced computer (numerical) simulation tools, ABB maintains the highest quality control of its products, and minimizes the development time of new products. These simulation tools allow engineers to explore thousands of design alternatives within very short time periods, leading to improvements in performance and design quality, and reducing the time required to bring a product to market.

1 Results from simulations of epoxy casting and polymerization process

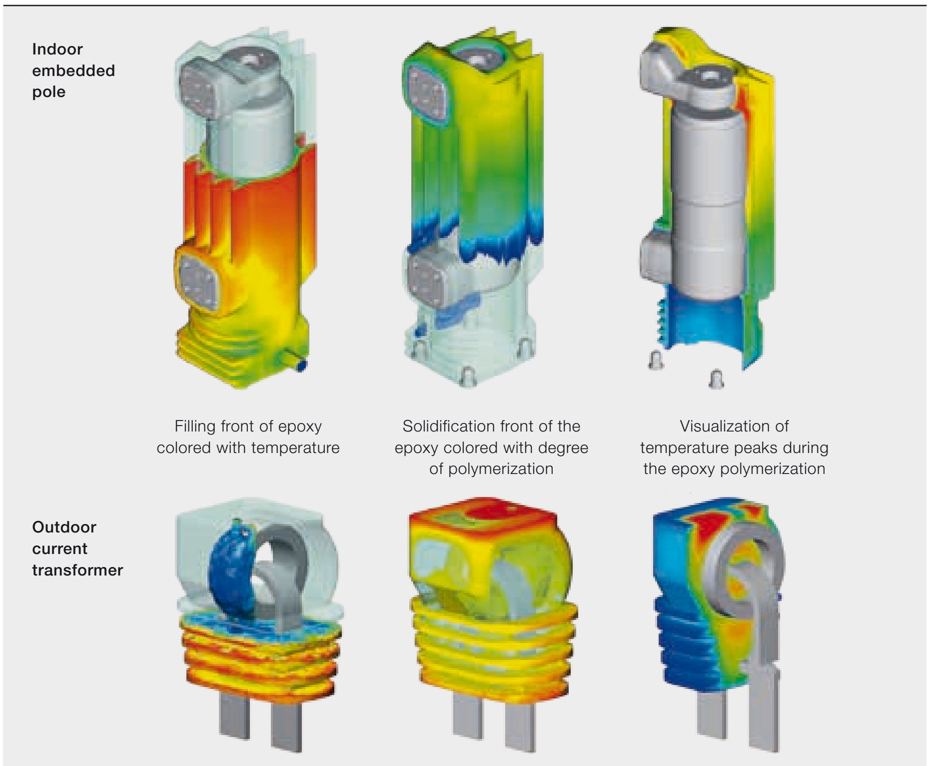


ABB uses advanced computer simulations in all of its polymers processing technologies, including reactive molding, injection molding, and silicone molding.

Epoxy casting

Epoxy resins are the principal insulating material used in manufacturing ABB's medium- and high-voltage products. The complex manufacturing process, referred to as reactive molding, includes casting, gelling (solidification) and cooling. By using a multiphysics approach that brings together advanced computer simulations of fluid flow, heat transfer, mechanical deformation and stresses, more accurate results are achieved and engineers are better able to follow and control the manufacturing process.

They can observe the mold filling with epoxy resin, the material transition from liquid to solid state, temperature distribution with temperature peaks caused by exothermic chemical reaction, shape deformation during the cooling and related buildup of stresses [1, 2] ➔ 1. Detailed analysis of the obtained results helps in selecting the best process parameters. Maintaining the right processing temperatures and minimizing the residual stresses are the key factors that determine the final product quality and reliability.

ABB has also developed a Web-based epoxy casting simulation tool that offers fully automated calculations [3]. The calculations can be performed directly by design or process engineers with no numerical modeling background. The mesh generation, simulation setup, calculations and other steps are done automatically based on input variables like model geometry, selected materials and process parameters. The tool generates a report with a summary of the results that can be used to analyze the process regarding its quality and efficiency.

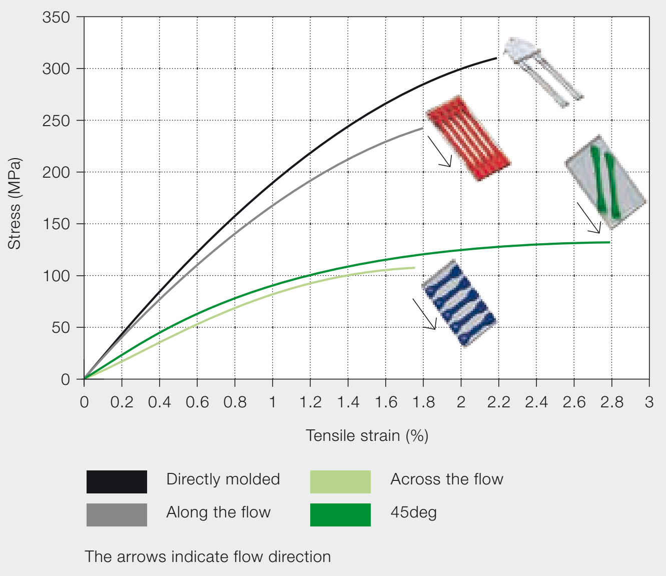
Thermoplastics injection molding

Thermoplastic polymers, used predominantly in ABB low-voltage products, are distinguished from epoxies and other thermosets by their ability to be melted and molded when heated above certain temperatures, returning to a solid state upon cooling. Injection molding is the most common processing method for thermoplastics. Hot, melted polymer is injected at high speed (up to hundreds of cm^3/s) at high pressure (up to 2,000 bars) into a cold mold cavity; while the polymer is cooling, the pressure is maintained by the injection unit in order to compensate for shrinkage. When the polymer temperature is 20 to 30 °C below the solidification temperature enough mechanical strength has been gained so that the part can be ejected. Production cycle time depends on wall thickness (starting from 0.5 to 6 mm) and usually takes from a few to around 100 s. Part and mold design is very challenging because of the complex phenomena occurring during thermoplastics processing – eg, shearing, viscous heating, crystallization, orientation,

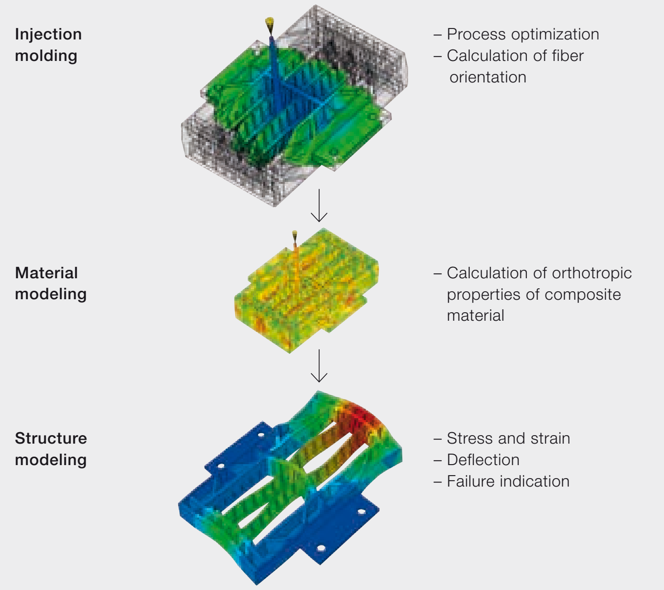
To maximize the composite potential in the development of its thermoplastic components ABB uses advanced simulation.

Title picture
Optimization of a sample component achieved with injection molding simulation.

2 Comparison of tensile test results for polyarylamide 50 percent glass fibers in the case of different orientation of short fibers



3 Simulation approach for short fiber reinforced thermoplastics processed by injection molding



Advanced computer simulations are conducted in order to optimize each part and mold design before mold fabrication.

cooling and undesired deformation (warpage).

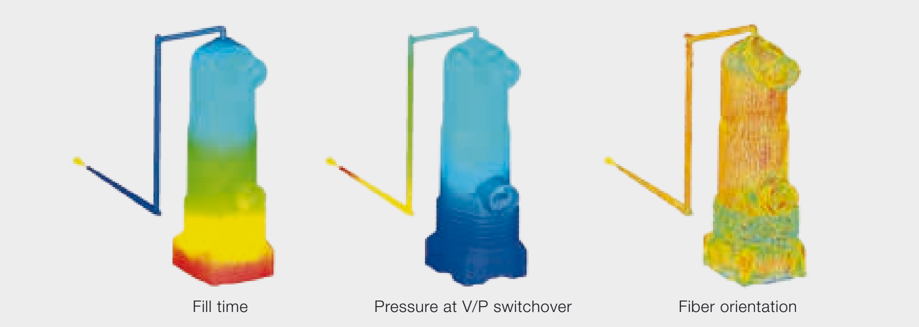
Advanced computer simulations are conducted in order to optimize each part and mold design before mold fabrication. The computer simulation tool allows analysis of all the processing stages: injection, packing and cooling (ejection time and its impact on heat distribution in the mold is even taken into account). The simulation model considers all the essential components of the injection mold, such as part cavity, cold or hot runner system, part or mold inserts, cooling circuits, and mold venting if necessary. Computer simulations help evaluate the quality of the injection stage in terms of filling profile, flow stagnation, premature polymer freezing or location of weld lines and air traps. During the packing and cooling stages the efficiency of shrinkage compensation is evaluated so that the correct selection of a cold gate cross-section can be made. The shape of the final part is also modeled by taking into account warpage caused by the polymer shrinkage, uneven cooling and material orientation.

The software used for injection molding simulation includes a database with over 6,000 predefined thermoplastic materials, which can be used for material specification – eg, pressure-volume-temperature (PvT), viscosity as a function of temperature and shear rate, and thermal and mechanical properties. The software also handles processes like gas-assisted injection, injection compression, co-injection and fiber-reinforced materials.

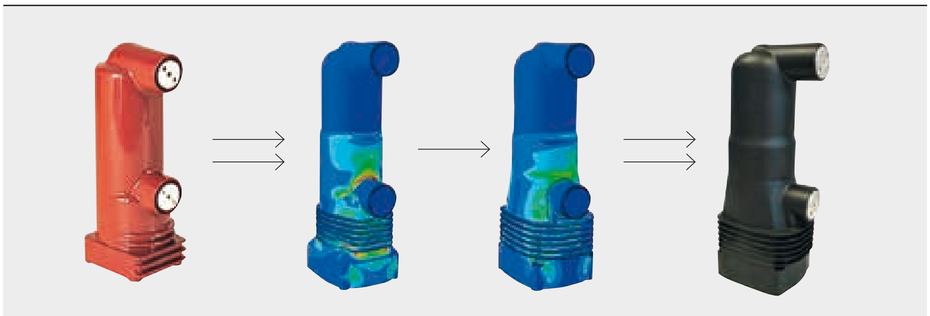
Thermoplastic composites reinforced with short glass fibers are also often used as insulating material because of their excellent mechanical and thermal properties. Introducing these materials into a product is challenging because the short fibers in a polymer matrix are aligned in flow direction during the injection-molding process resulting in anisotropic material properties. The highest stiffness and strength is measured in the direction of material flow during molding, while the transverse performance could be only 35 percent of material datasheet values (based on measurements for polyarylamide reinforced with 50 percent glass fibers) → 2.

To maximize the composite potential in the development of its thermoplastic components ABB uses advanced simulation → 3. The first step of the simulation process is to gather information on fiber distribution. Material properties of polymer matrixes and fibers are defined separately in the material modeling software, which calculates the resulting mechanical properties of the composite. These values are then used by a structural simulation package to calculate product response under applied mechanical load. Estimating the critical load that can be carried out by the composite material becomes feasible with stress- and strain-based failure indicators [4, 5].

4 Simulation results of injection molding process of thermoplastic embedded pole



5 Mechanical optimization of thermoplastic embedded pole structure



The dielectric performance of the design is checked with the simulations of the electric field distribution.

From epoxy to thermoplastics

Thermoplastic materials have been widely used in low voltage products applications. With the increasing capabilities of engineering thermoplastics, they are also being considered as a replacement for thermoset epoxy insulation for higher voltage level products. The mechanical properties of engineering thermoplastics are much better than of epoxies, with significantly higher stiffness and several times higher mechanical strength. The dielectric strength of the thermoplastics can also be superior. These strengths allow for significant reduction of the product weight and environmental impact.

ABB's PT1 embedded pole is an example of switching from epoxy to thermoplastics in ABB's medium voltage applications. Changing the insulation material results in a weight reduction of more than a factor of three while gaining superior mechanical performance. The material change reduces CO_2 emissions in the product life cycle by more than 50 percent [6]. All these improvements have been achieved by using advanced computer simulations.

Injection molding of thermoplastics is better suited for thin-walled parts in contrast to the bulky structures of epoxy components. Therefore when a material change needs to be made for a medium or high voltage product, a complete redesign of the product is needed. The first stage of a redesign is to create the design ideas and then a draft design of the plastic part. Then the evaluation and optimization of the concept is carried out with simulation tools. In the mechanical analysis all the load cases to which the product is subjected during its operation are modeled. In parallel, the manufacturability of the part is verified with simulations of the injection molding process → 4. The dielectric performance of the design is checked with simulations of the electric field distribution. Based on simulation results, modifications are introduced to the design and the next cycle of simulations is started. Based on the final results, the prototype of the part is manufactured and subjected to all tests required by standards.

Computer simulations allow engineers to look inside the injection mold for a complete picture of how the silicone rubber is processed.

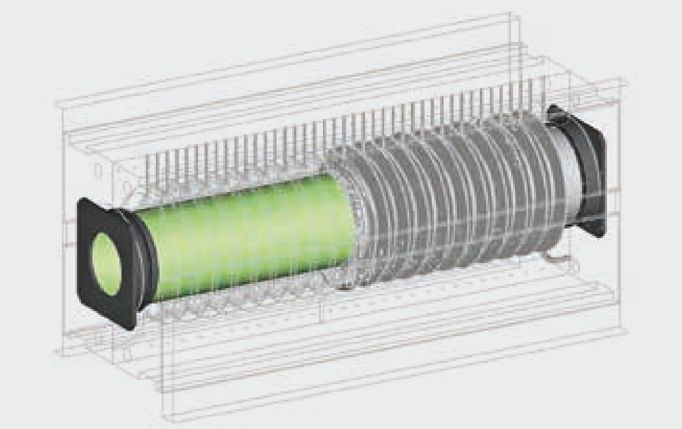
With ABB's thermoplastic embedded pole, such an approach allows for a 50 percent decrease of the maximum stress level in the part → 5. By using the injection molding simulation the process settings are optimized and the material pressure in the mold cavity is reduced, which is important in this application as the overmolded vacuum interrupter was designed for low pressure casting process. With the computer simulations both the design of the thermoplastic embedded pole and its manufacturing process were optimized.

Liquid silicone rubber processing

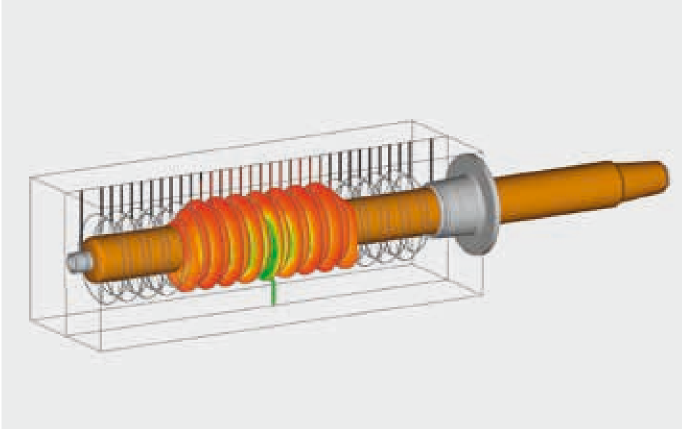
Silicone molding is another processing technology extensively used for producing electrical insulation in medium- and high-voltage power products like surge arresters, bushings, insulators and cable terminations. The excellent properties of silicone rubbers include high chemical and thermal stability resulting in the material hydrophobicity, UV stability as well as good flashover and erosion resistance [7, 8].

Another factor influencing the properties of the silicone insulation is the material processing during the insulation manufacturing stage.

6 Flow pattern and curing for HV silicone insulation



6a Flow pattern of silicone during mold filling



6b Course of curing process of silicone

One of the possible threats connected with silicone molding is too high temperatures during the process that can cause degradation of the material properties. Good temperature control is even more important when taking into account the exothermy (heat generation) during the silicone curing, which might lead to creation of local hot spots. Besides that too severe temperature conditions can result in premature gelation of the silicone rubber and, consequently, in incomplete filling of the mold. Finally, incorrect design of the injection and ventilations systems can create air gaps during the mold filling, creating partial discharges in the operating product.

Computer simulations allow engineers to look inside the injection mold for a complete picture of how the silicone rubber is processed [9, 10]. For example, the silicone flow pattern, pressure growth, temperature field and silicone cure degree can be observed over time → 6. These results can be further used to recognize the potential problems connected with product design or its manufacturing process. Computer simulations can be applied to work out the improved product design and production process in shorter time periods and with lower investment costs.

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Further reading

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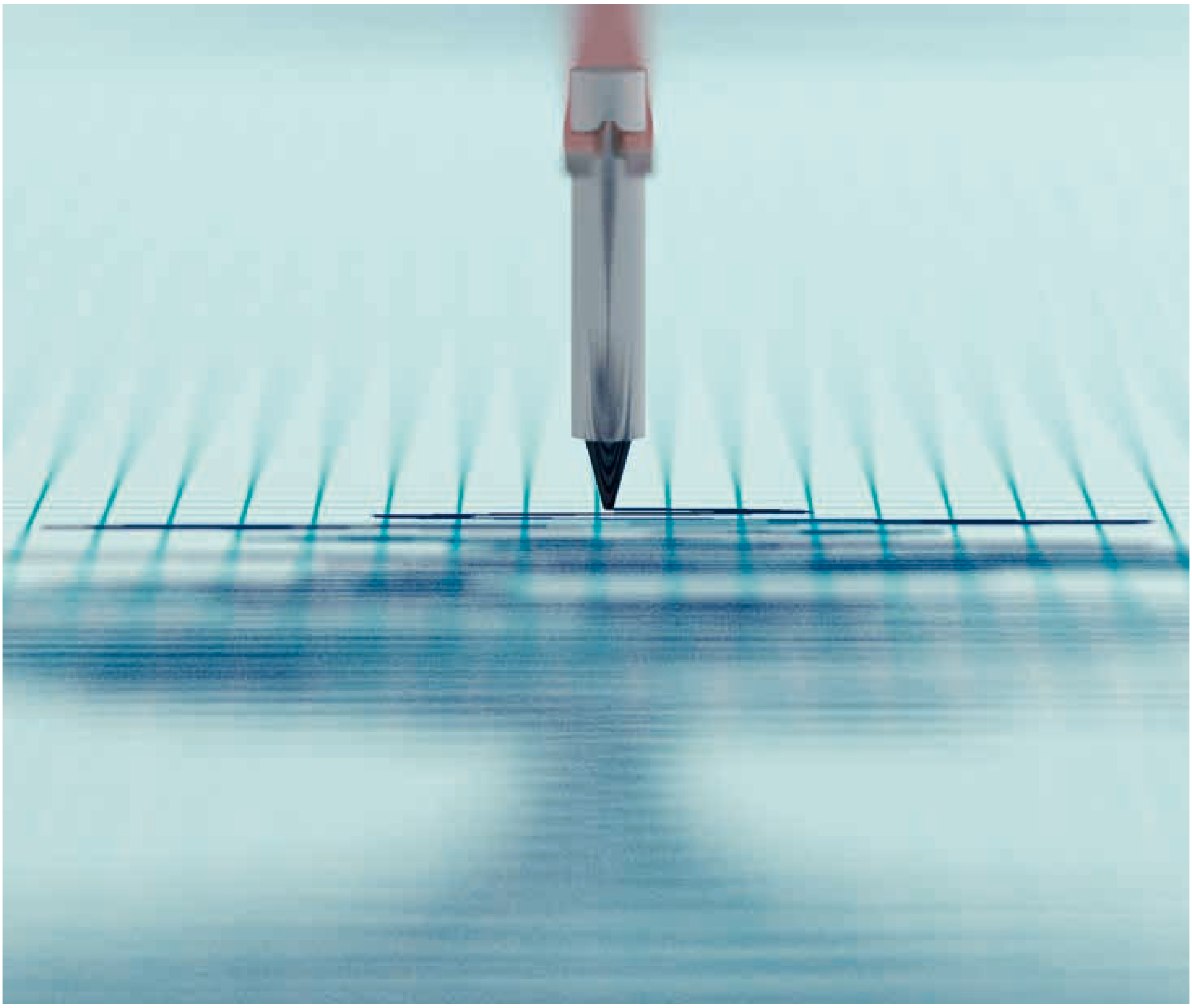


Shake, rattle and roll

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.

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.

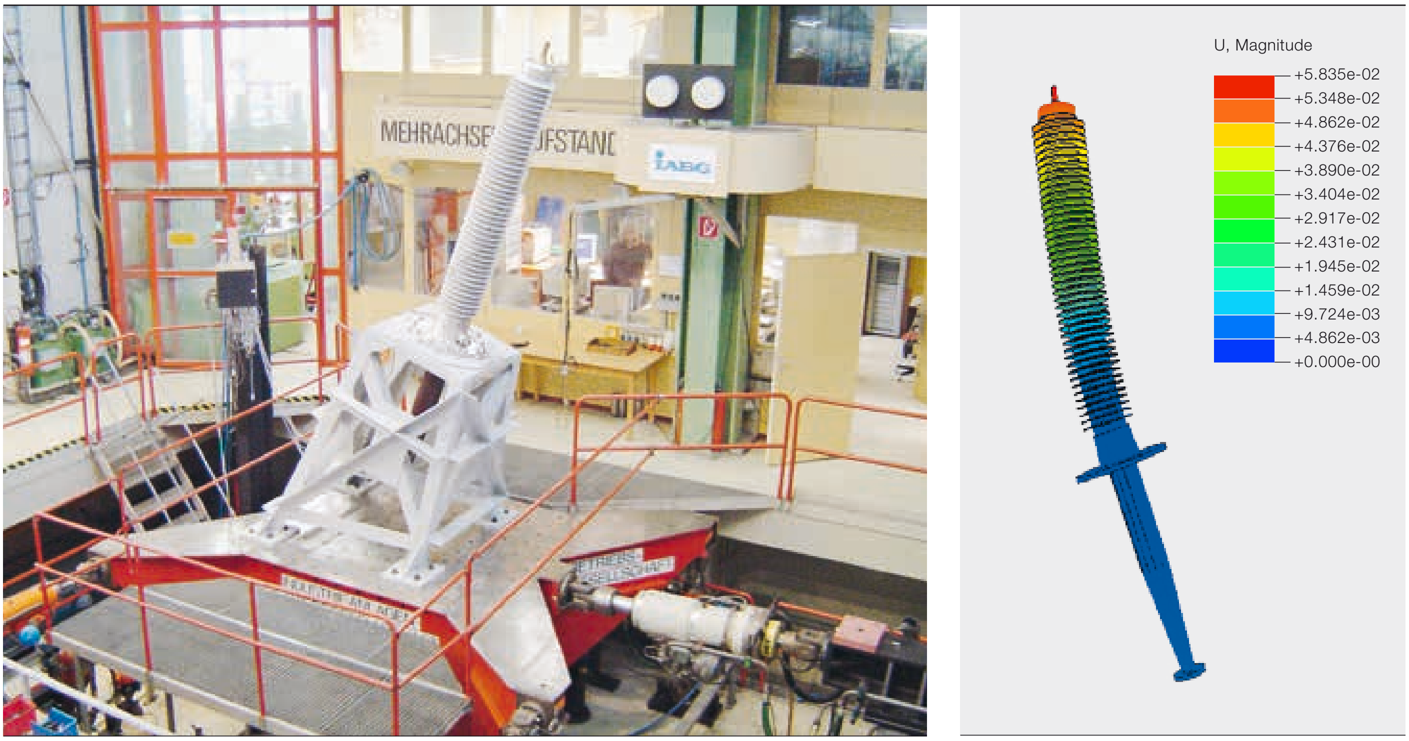
Modeling methods for seismic analyses

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

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.

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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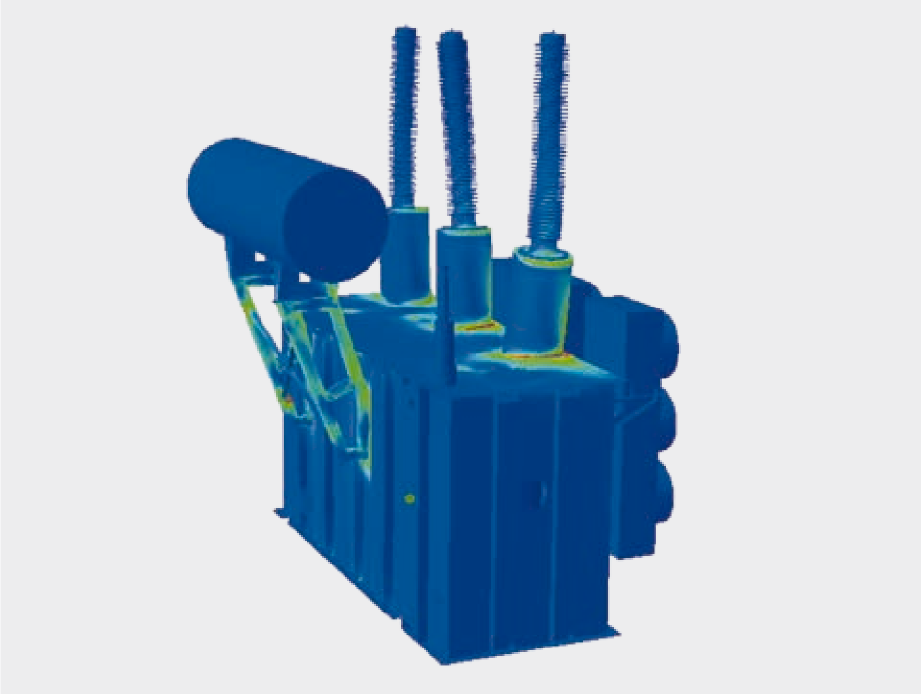
2 Stress distribution of the whole power transformer during seismic analysis



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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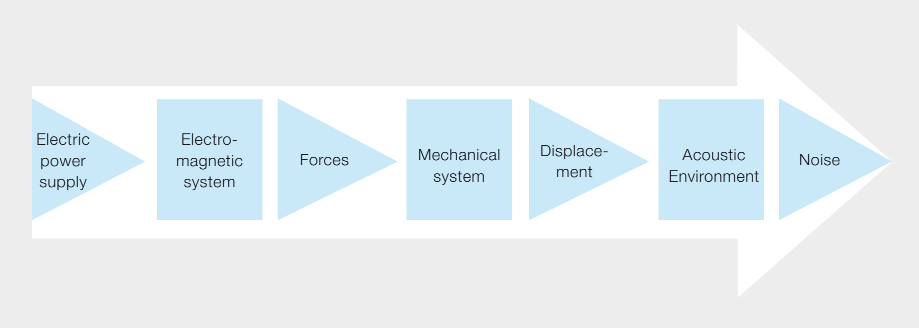
Vibro-acoustic simulation examples

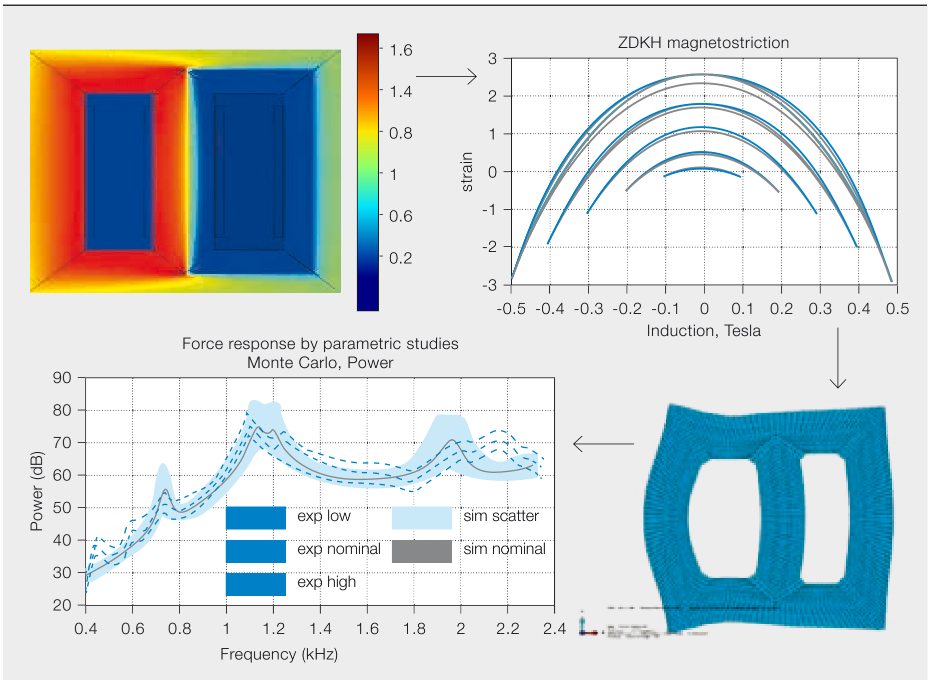
At ABB's research centers, finite-element and boundary-element methods are used to simulate the vibro-acoustic performance of various ABB products. The typical example of multiphysics and multiscale simulations is the noise generation in oil-immersed power transformers where two particular sources of 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



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.

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.

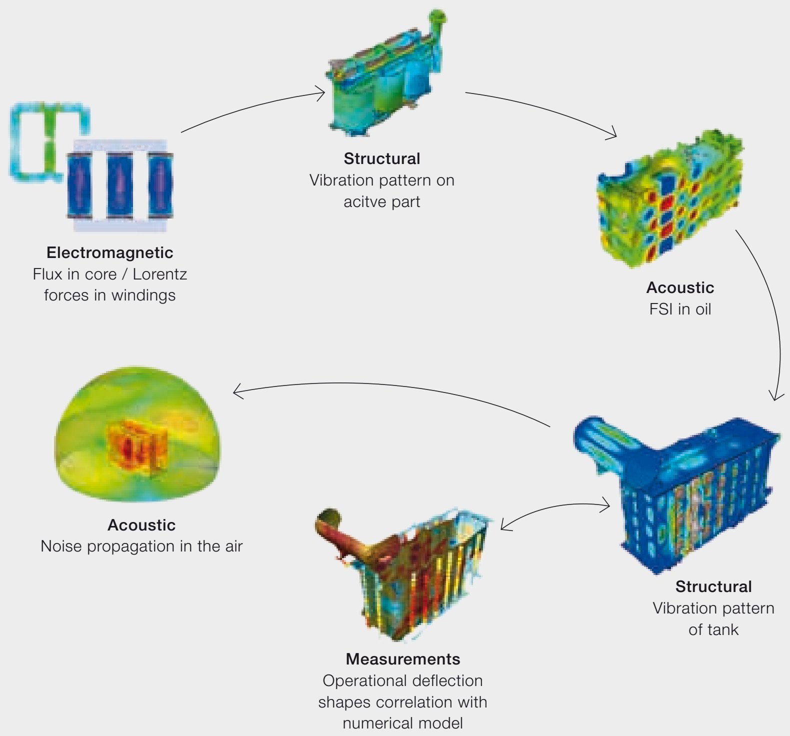
→ 4 presents a typical approach for a transformer-like product. The procedure starts with the electromagnetic calculations, which give mechanical forces applied to the structure. Crucial for appropriate vibration image on the tank is the structure-fluid-structure path, including interface and phenomena 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.

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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Data centers

Computers and the Internet are not only transforming the way humans work and interact, but are continuing to develop at an astonishing rate while both finding new applications and revolutionizing existing ones. Whereas progress in computing was once typically in purely statistical terms such as by Moore's Law, progress today is much more tangible through the rapidly developing landscape of online services ranging from social media to online banking and commerce. Consumers can easily assume that these online services are mainly about interfaces and usability. But what the user sees is but the tip of the proverbial iceberg. Data centers across the globe are continuously processing and exchanging information and fulfilling ever increasing demands.

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