Simulation tools for the ACS 1000 standard AC drive

Computer simulation played an important role in the development of the ACS 1000, ABB's new standard AC drive for medium-voltage applications. Not only the complexity of the tasks and the diversity of the products called for a powerful simulation tool, but also the cost and time targets that were set. The Saber simulation engine met all the requirements in full and provided the required verification of agreement between the models and practice. Thanks to the combination of simulations and tests in the power laboratory, the robustness and reliability of the design could be significantly improved. Optimization for a wide range of applications was possible as a result.

ACS 1000 is the name of a new standard AC drive 1 from ABB which can be used for the majority of medium-voltage applications [1]. It is designed for the power range of 315 to 5000 kW and voltages of 2.3, 3.3 and 4.16 kV, and can easily be adapted to meet special requirements. Also, the time needed to install and commission it is comparatively short. The drive is typically used with pumps, fans, compressors and conveyor systems, which together make up approximately 85 % of the total market in this power class.

Power section of the ACS 1000

The ACS 1000 is a completely new product in every respect. The fact that no predecessor had been designated as a technical platform meant that completely new, innovative and future-oriented technologies and ideas could be implemented in it.

The new drive incorporates Direct Torque Control (DTC) [2], which had already been used successfully in the ACS 600 [3]. The concept adopted for the power section of the ACS 1000 2 has the following features:

- Three-level inverter: no series connection of the semiconductors, simple design
- Integrated Gate-Commutated Thyristors (IGCTs) [4]: no parallel connection, fast switching, low losses, no d*u*/d*t* snubber, integrated gate unit, reliable, robust
- Common mode choke: suppresses and controls the common mode currents that occur wherever converters are used
- Output sine filter: sinusoidal output voltage and currents, suitable for retrofits, no reflections on motor cable, no stressing of motor insulation, no problems with EMC
- 12-pulse input bridge (24-pulse as option): satisfies IEEE 519, low power system harmonics
- Small number of components: high reliability, availability better than 99.9%, highly compact construction

Gerhard Bräuer
Adrian Wirth
Gerhard Wild
ABB Industrie AG

Dr. Heinz Lendenmann
ABB Corporate Research

Why simulation is necessary

Modern simulation tools offer a whole range of technical and economic advantages (see box).

Of the different converter types, only a few are built as prototypes, then tested ('real prototyping') and verified by simulations that run parallel to the tests. The remaining types are dimensioned and verified with the help of simulations ('virtual prototyping'), plus a type test.

Technical and economic advantages of simulations

Technical advantages
- Determination of the fundamental system behaviour
- Shorter learning cycles
- Dimensioning of different components
- Analysis of critical items (faults, protection functions)
- Improvement and optimization

Economic advantages
- Shorter time needed for development
- Cost optimization (virtual prototyping)
- Avoidance of bad investments
- Reduction in tests needed

ACS 1000 standard AC drive for medium-voltage applications **1**

The simulations used to verify the information on the ACS 1000 data sheet also checked its validity for actual installations with more critical parameters. The parameters that influence a converter system, its design and its dimensions are as follows:

- Power supply system
- Input transformer
- Linear electric constant of the cable between the transformer and the converter
- Linear electric constant of the energy cable to the motor
- Motor parameters (voltages, power rating, pole number up to max 20, power factor)
- Different loads

Why Saber was chosen for the simulations

The decision to use Saber, a product of the firm Analogy in the USA, as the simulation tool was taken already at the initiation of the ACS 1000 project in January 1996. The decision was based in part on the following advantages it offered:

- Mixed-technology simulation, allowing diverse electrical, mechanical and hydraulic systems to be simulated together.
- Mixed-signal simulation, in which analogue and digital quantities can be simulated at the same time.
- A powerful hardware description language, called MAST. Without this language, the high quality of the models and simulations would never have been achieved.
- An interpretive scripting language, called AIM, for creating powerful macros. User-specific tools for simplifying the simulation tasks were realized with macros.
- Saber know-how already gained at the ABB research center in Switzerland.
- Saber's outstanding user-friendliness.

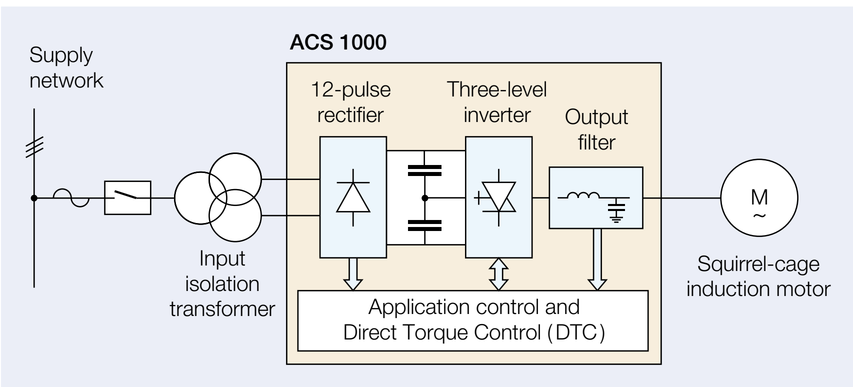
The Saber engine provides powerful support in the development and engineering areas. Applications offered by the Saber-Designer tool are as follows:

- *SaberSketch* Design entry and editing
- *SaberGuide* Interactive simulation control
- *SaberScope* Graphical waveform analysis
- *SaberSimulator* Mixed-signal, mixed-technology simulation

Saber – a sub-project of its own

It was clear already during the start-up phase that the planning of the simulation activities would have to be detailed and ongoing. Detailed planning of the Saber application is a prerequisite for efficient and professional use. A team of Saber specialists **3** was responsible for

Circuit diagram of the ACS 1000 standard AC drive **2**



creating the models and for carrying out and coordinating the simulations. By adopting this approach, the simulations can be used to perform development tasks as well as to answer customers' technical questions.

The cost/benefit ratio has to be estimated and re-evaluated for every special analysis. During the development phase, efforts concentrated mainly on the following areas:

System simulations

- Generation of the electrical schematic
- Loss calculations and efficiency
- Loading procedures
- Clamp design
- Self-excitation
- DTC implementation
- Common mode behaviour
- Simulations accompanying tests (exact reproduction of the test rigs)

Protection simulations

- Rectifier defects
- Short circuits in the motor winding
- Response to earth faults
- Other short circuits
- Inverter protection

Saber simulation and ACS 1000

To help the personnel to familiarize themselves with the simulation tool and to work efficiently and manage the parameter sets of the different converter types, a special user-interface was created called the ACS 1000 Simulation Manager **4**.

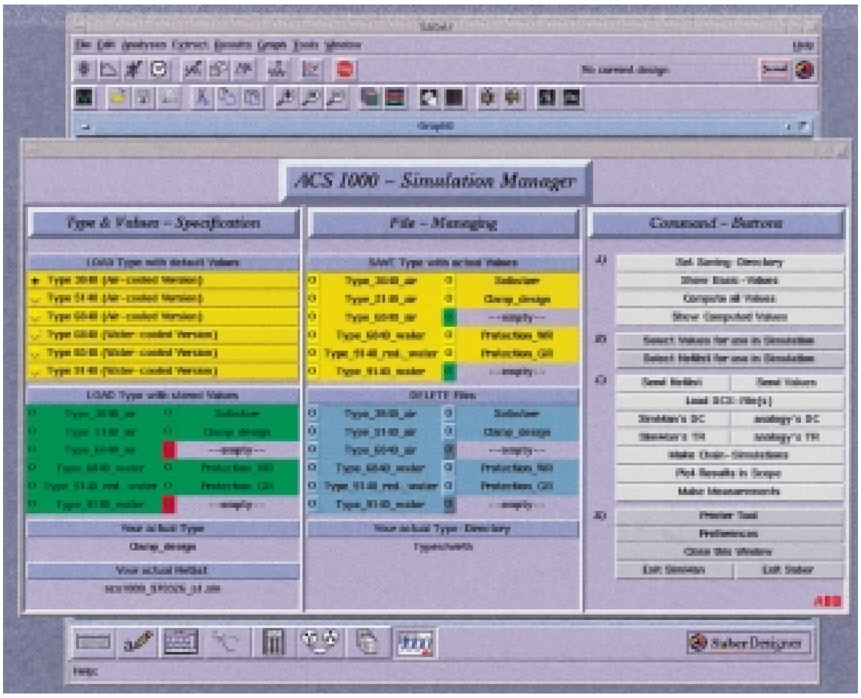
The Simulation Manager is loaded into the graphic user-interface, after which it can be accessed by clicking on an icon. Menu-driven, it acts as a highly user-friendly interface to the Saber tool. Via this interface, it is possible to quickly change the parameters in a schematic, calculate certain variables directly using formulas, and automate simulation runs and evaluations.

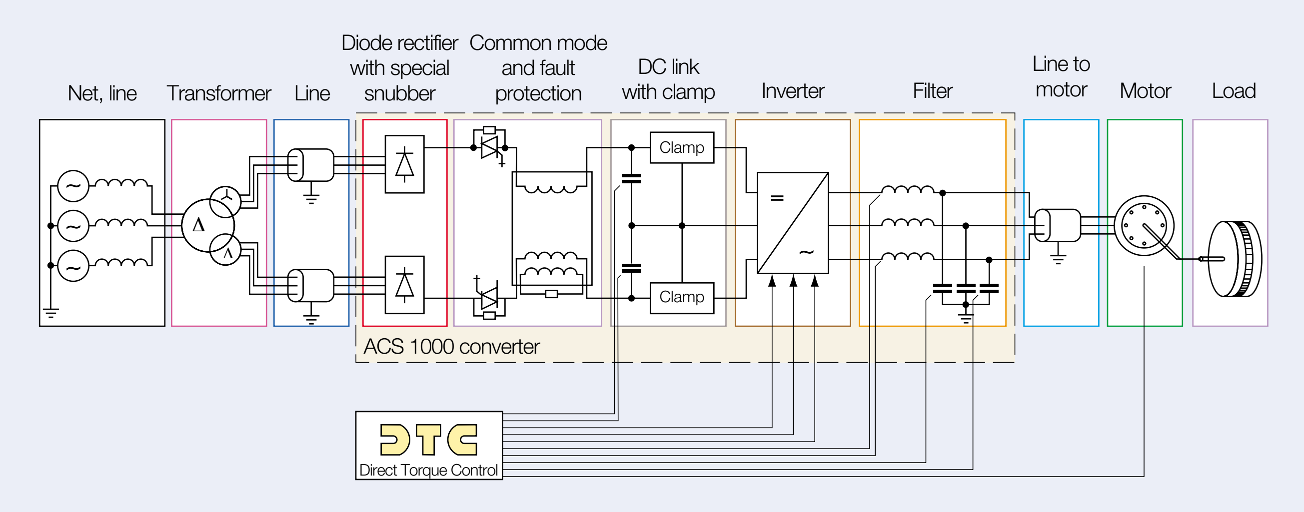
An important preliminary to any given simulation task is the selection of the appropriate schematic. The requirements that have to be satisfied by the schematic and the components included in it depend on the nature of the problem. Other criteria which have to be taken into account are the computation run time and the simplifications in the model which are allowed. Three examples of these are given below:

- The Saber libraries did not contain a diode with the reverse behaviour of the new IGCT. The models available for this purpose could only inadequately repro-

Development engineers at a workstation **3**

ACS 1000 Simulation Manager **4**





Block diagram of the ACS 1000 **5**

duce the diode characteristic. It was soon realized that priority would have to be given to a stable converging model requiring only little computation run time and capable of reproducing the curves as accurately as possible. Such a model was created in the ABB research center using a mathematical adaptation. By taking account of the special properties of the IGCT and its diode it was thus possible to obtain a sufficiently good model in terms of waveshape, computation run time and convergence stability.

- Data on the power losses to be dissipated were needed in order to design the cooling system. Measurements in the laboratory enabled the turn-on and turn-off losses of the semiconductor devices to be determined. On the basis of these measurements 'lossy' switch models were written in the model language; these calculated the losses as a function of the switching voltage and current. The 'lossy models' were then applied to a modelled converter phase and controlled via DTC. In this way it was possible to obtain a formula for calculating the losses which takes into consideration the DC link voltage, phase current and switching frequency.
- The inverter in the ACS 1000 is driven by DTC [2]. DTC provides the control signals for each switch in the three converter phases. The DTC algorithm is implemented in Saber **5**.

Because of its complexity, the DTC control platform is featured in Saber as an 'hierarchical model', ie it contains further components in subordinate schematics. Some of these components, referred to as templates, had to be written especially in the MAST language.

The DTC model was verified in an initial phase by means of measurements. This enabled important information to be obtained about the component stresses and variables which are difficult to measure, and therefore also about the quality and reliability.

Converter parameter data sets for the simulation schematics

The components in the schematics can be parameterized for every type of converter. Parameter files containing the values of all the component variables (capacitors, chokes, resistors, leakage reactances, cables, power system and transformer, etc) exist for the entire product series. The Simulation Manager makes it considerably easier to manage and update these files. ABB has today an impressive library of parameters for every converter. With the help of these files it is possible to simulate the entire product series using just one schematic.

Computation run time and accuracy

To be able to evaluate the simulation results it is important to know how accurate they are. Any consideration of accuracy must distinguish between the simplifications allowed in the schematic and in the models as well as take account of the accuracy set for the simulator.

The right schematic for a given problem

The simulation schematic for most of the set tasks was created by ABB. As a result of this, the processes can be reproduced in the simulation in an optimum way and with the necessary attention to detail. Today ABB has an adequate library of schematics of its own.

Models of all test rigs

To obtain qualitative feedback from the Saber simulations, all the test rigs and production test facilities were implemented as schematics. As a result, the simulations and measurements could be compared exactly. This was very important as a means of confirming the accuracy of the simulator and the correctness of the generated models, and ultimately of the overall performance of the team. The model generation covered the power system, transformer, feeder lines, converter, motor and DTC platform.

Simulations were carried out in parallel with the tests to provide an economic and risk-free pre-analysis of the protection functions and forced faults tested in the laboratory. The load limits of the components could therefore be determined without risk and incorporated in the specifications. This allowed the number of required IGCT test patterns, which at the time were not available in large numbers, to be minimized.

The quality of the agreement was convincing and confirmed the design based on the simulations 7a, 8a, b, c.

Verification of the protection concept

A new protection concept was also developed for the ACS 1000 which took special account of the properties of the IGCT and the power section of the new drive. Using the results of the simulation as a basis, it was possible already during the conceptual phase to test and evaluate the properties and effectiveness of the protection equipment. For example, it was recognized already at this early stage that fuses offer inadequate protection in the case of certain simulated semiconductor failures. This was due especially to the relatively long time that elapsed before the main circuit-breaker opened and the resulting flow of energy from the transformer. A wide variety of protection concepts without fuses were tested with the simulator. The ideal solution was shown to be so-called 'protection IGCTs' in the DC link in combination with an innovative RC network for the rectifier, which has meanwhile been patented.

In another example, a test was carried out to verify that the converter is also able to handle external faults, such as short circuits at the motor terminals 6.

Harmonics and power quality

As a supplier of medium-voltage converters, ABB not only has extensive experience in the areas in which converters are used but also of the problems which can be caused by perturbations in the power supply network. The computer simulation and the method of calculation developed on the basis of it allow the harmonics in the supply system to be determined accurately for any converter in the ACS 1000 series and for any working point. If inadmissible values for the converter harmonics are determined, they can be reduced by means of special filters or by changing the impedance of the feeder transformer.

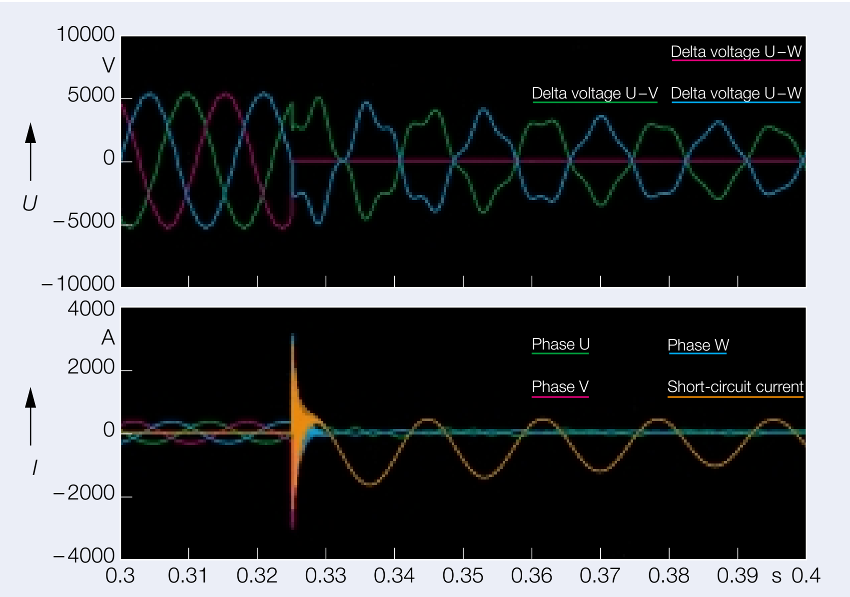
To reduce the 5th and 7th harmonics from the outset, the ACS 1000 is equipped on its input side with a 12-pulse (option: 24-pulse) input transformer and rectifier. The measured and simulated input current is shown in 7a.

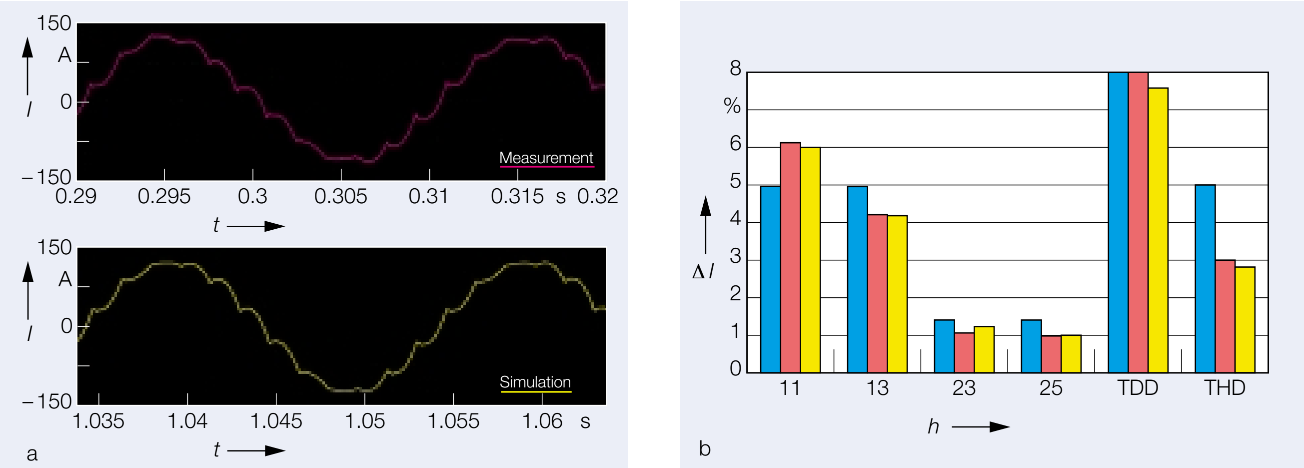
7b shows the agreement between the measured and simulated characteristic harmonics (11th, 13th, 23rd, 25th). With this input transformer, the requirements laid down in IEEE 519 for the 11th current harmonic would not have been satisfied. Since the simulation is able to reproduce the behaviour of the complete converter with high accuracy, it is a simple matter to determine the minimum transformer impedance required and therefore obtain optimum specifications for it 7c.

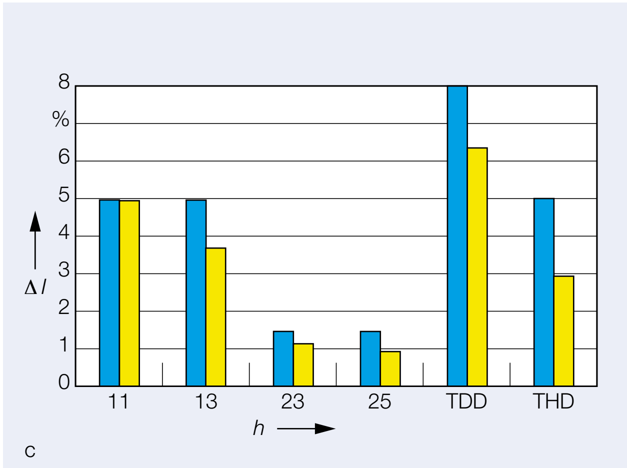
Output sine filter

8a shows the unfiltered line-to-line voltage of the three-level inverter, both measured and simulated. The filter eliminates all the

Two-phase short circuit at motor terminals and subsequent blocking of the inverter pulses **6**







Simulations and measurements used to determine the harmonic load caused by a 1250-kW drive at a voltage of 4.16 kV **7**

a *Input variable: power system phase current*
b *Characteristic harmonic of power system current when transformer impedance voltage is too low*
c *Characteristic harmonic of power system current with required transformer short-circuit voltage*

ΔI *Current distortion*
h *Order of harmonics*

Blue *Permitted by IEEE*
Pink *Measurement*
Yellow *Simulation*
TDD *Total demand distortion (current)*
THD *Total harmonic distortion (voltage)*

higher-frequency components of the output voltage **8b** and output current **8c**.

Common mode choke

Every inverter produces common mode voltages. In the case of the ACS 1000, these are kept away from the motor by solid earthing of the filter star point. As a result, they appear at the output terminals of the supply transformer **9**. The capacitances of the cable between the transformer and converter are therefore continually recharged, causing earth currents to flow through the customer's installation. Earth currents of this kind appear wherever inverters are installed and are attenuated in the case of the ACS 1000 by a special common mode choke. This choke ensures the full functionality of the converter for feeder cables up to 300 m in length.

Benefits and experience

Due to the many different types of ACS 1000 converter and the ambitious targets that were set for the project, simulations were planned as part of the development programme from the beginning. Their variety was used to estimate how many people should make up the team and what the investment costs would be. Before Saber could be used, however, questions concerning the operating system, hardware, network, licences and data security had to be answered. Confirmation of the level of investment needed and its significance, however, came only later in the project.

In retrospect, it has been confirmed that there is considerable benefit to be gained from the close collaboration between the Saber team and the hardware and software development engineers, and that it helps a project of this kind to be completed in a shorter time. Although there were problems initially with the simulation capability, a fully functional simulation environment existed then when demand for simulation capacity was at its highest. Thus, not only could all the set tasks be carried out but customer-specific simulations could also be performed for the sales department. The decision to include Saber in the ACS 1000 development programme proved to be right in spite of the work and costs involved.

Benefits of Saber during series production

While a simulation tool such as Saber can help to build confidence in the design of a product during its development, it offers a much wider range of uses. The results obtained from simulation give valuable support in other areas, such as application and sales, and also helps in the optimization of a product and in extending its functionality.

Application

Saber offers indispensable support for investigations into system-specific problems. For example, the time between a problem appearing and its elimination can be minimized without having to invest in complicated and costly laboratory set-ups. With a tool like Saber, electrical, mechanical or hydraulic processes as well as special cases in a system, can be understood in depth in just a short time, allowing correct measures to be taken quickly.

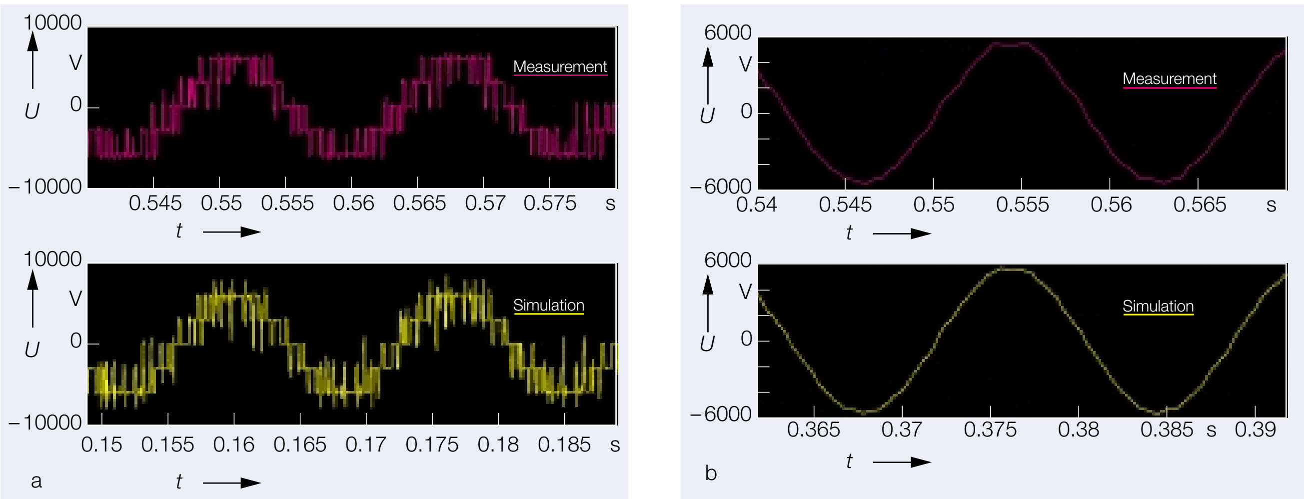
Reliability can be improved already during the development phase by means of redundant design checks, simulation and laboratory tests. Uncertainties can be clarified much faster with the help of simulations than with complicated and time-consuming measurements in the laboratory.

While simulations cannot replace a laboratory, they offer invaluable benefits whenever a fast and efficient response to system-specific problems is required.

System simulation as back-up

With Saber, it is possible to simulate a potential customer's system and test how the ACS 1000 will interact with it. Complicated or critical network configurations can also be easily simulated. Due to growing concern about power system perturbations it is very important to be able to predict them before start-up and so enable a proactive approach rather than having to take corrective action in the installed system later. Unpleasant surprises during commissioning of installations can be minimized up front, while the commissioning itself can be carried out faster and at a lower cost.

Customers whose products have to fulfil certain special requirements (eg, individual protection, an above-average lifetime



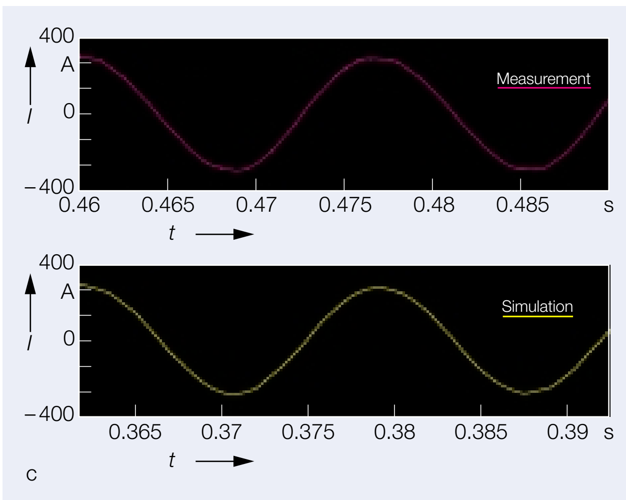
Consequences of the output sine filter **8**

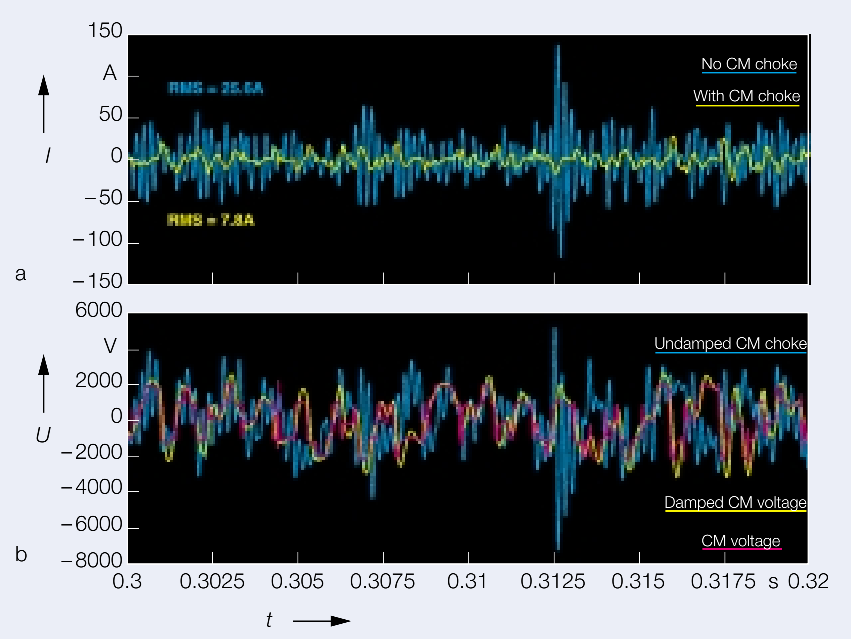
Load: 1250-kW motor, 4.16 kV

a *Inverter output voltage without sine filter*
Operating standard motors with this unfiltered voltage would call for attention to:
- *Voltage reflections at motor terminals*
- *Accelerated aging of the motor insulation*
- *Higher additional losses in motor*
- *EMC problems*

b *Output voltage of ACS 1000/motor voltage*
The sine filter keeps steep voltage slopes (10–20 kV/µs) and harmonics away from the motor, thereby eliminating the above disadvantages.

c *Output current of ACS 1000/motor current*





Influence of the common mode choke **9**

a	*Influence on earth current*
Blue	*Without common mode choke*
Yellow	*With common mode choke*
b	*Influence on common mode voltage*
Blue	*Unattenuated common mode voltage*
Yellow	*Attenuated common mode voltage*
Pink	*Common mode voltage*

or a non-standard specification) can be served faster and more reliably as a result of the more efficient development work which is possible with Saber.

System optimization and extensions

When optimizing a product special priority is given to its availability and reliability, which should be as high as possible. The test equipment used in a power laboratory reflects only one case taken from practice. This one case is important and can assist in the generation of the simulation model; in addition, the results of the simulations and measurements can be compared. Robustness, reliability and safety can all be improved as a result.

Dangerous types of fault or destructive tests can also be analyzed in advance without risk, and their consequences estimated. This safety aspect is of immense importance.

The customer's environment (ie, the interfaces) may be quite different to the laboratory environment. The properties of the supply network, feeder cable and interposing transformers in a proprietary test laboratory are never the same as in a customer's installation, although the same components can have a large influence on the behaviour of a product within a system. With the described simulation engine, it is possible to add the properties and characteristics of the customer's own system to the model and so achieve an optimization which is valid for a wide range of applications.

When developing a standard product it must be ensured that it will function trouble-free even in extreme situations. Thanks to the simulations that were carried out, this could be checked during the ACS 1000 project and the drive designed accordingly.

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Authors

Gerhard Bräuer
Adrian Wirth
Gerhard Wild
ABB Industrie AG
P.O. box
CH-5300 Turgi
Switzerland
Telefax: +41 56 299 34 00
E-mail:
gerhard.braeuer@chind.mail.abb.com
adrian.wirth@chind.mail.abb.com
gerhard.wild@chind.mail.abb.com

Dr. Heinz Lendenmann
ABB Corporate Research Ltd