ABB review

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The corporate technical journal

In this centenary year, *ABB Review* will be looking both forward and to its past. The perspective of history provides a greater understanding of the present and of the impact that ongoing innovations have over the years had on the company, the market and indeed society. The front cover photograph shows an ABB robot at work manufacturing ABB switchgear in Beijing, China. This page shows the Stromberg machine factory in Vaasa, Finland in the 1940s.

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Innovation

Claes Rytoft

Dear Reader,

2014 is a very special year for *ABB Review*: We mark 100 years since the first publication of our direct predecessor journal, *BBC Review*. A century is a long time, especially on the scale of technological developments, and the changes that the journal bears witness provide a fascinating documentation of 100 years of ongoing innovation. Throughout our anniversary year we hope to share with you insights from the past, along with (and sometimes through the eyes of) modern developments.

Opening its centenary year with an innovation issue, *ABB Review* is looking both to the future and to its past. It is thus fitting that one of the main articles discusses a novel way of measuring current using a very old discovery. In 1845, Michael Faraday observed that magnetic fields affect the polarity of light – an observation that for many years was considered a phenomenon of little applicable value. Today ABB is commercializing it as a means to provide accurate yet contactless current measurements.

ABB understands that to be able to operate successfully, our customers not only seek the most advanced technologies, but also need to be able to operate them reliably, economically and for a long time to come. An article on asset health management explains why this is a field of growing importance and how ABB delivers added value in this area.

Last year, *ABB Review* ran several articles on simulations, spotlighting how ABB's researchers use cutting edge technologies to deliver ever more sophisticated products. Continuing in this vein, four further articles on simulations are presented, covering topics ranging from breaker analysis to turbochargers. In a related approach, an article on the design and testing of a wind turbine generator provides a case study of unfolding innovation.

USB devices have become ubiquitous in our personal and work lives, yet their power chargers often clutter up our luggage and take up useful space around us. Have you ever wished for a more ready means to recharge them? We present an elegant solution: electrical outlets that integrate a USB connector.

This edition is rounded off with a look at history. In issue 2/2013, *ABB Review* revisited the company's 100 year involvement in power electronics. That article was strongly focused on the switching devices used, be they mercury valves or semiconductors. In the present edition, we tour the same history but from the rectifier perspective.

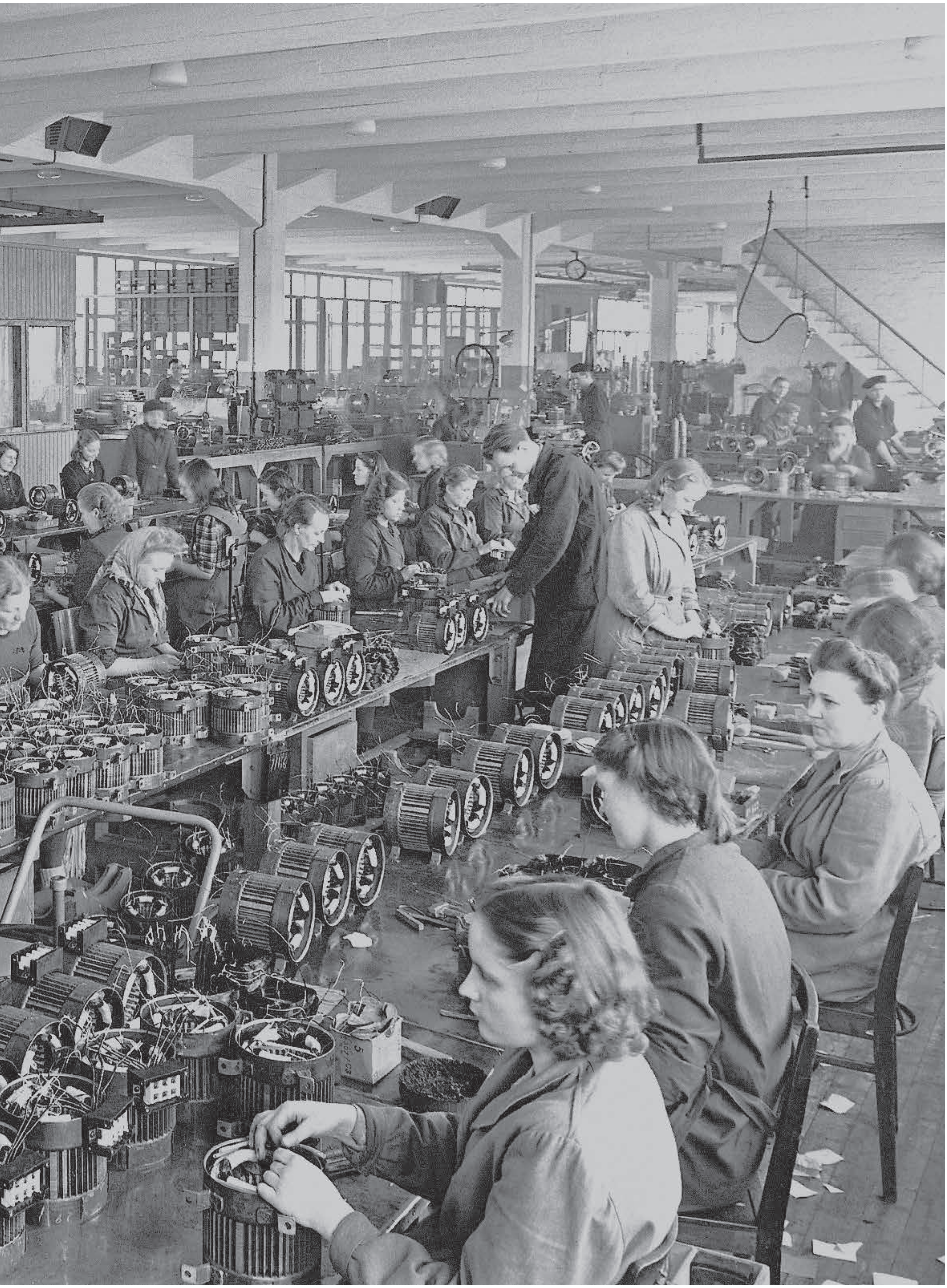
Finally, I would like to use this opportunity to remind readers that besides the print edition, *ABB Review* is available in electronic formats, both as pdfs and in more interactive versions for tablets. You can learn more about this on www.abb.com/abbreview.

Enjoy your reading.

Claes Rytoft

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

100 ABB review since 1914



Innovation highlights

ABB's top innovations for 2014

ABB is continuously working to strengthen its product portfolio and create new technologies to put its products at the forefront of innovation.

The current selection is a cross section of the company's innovative achievements. Many of these, as well as other technological successes, are discussed at greater length in this and forthcoming issues of *ABB Review.*

Increased battery life

ABB is developing truly wireless instrumentation that generates power by harvesting energy in the environment.

To overcome the short lifetime of batteries in wireless instrumentation, particularly at high-update rates, ABB is designing low-power devices, each powered by a normal D battery but with the ability to dramatically increase the battery life by harvesting the power from the process it is measuring. A very high efficient Peltier cell embedded in the transmitters will use the thermal gradient between the process and the environment to generate energy.

The ABB transmitter is powered by an onboard micro-thermoelectric generator (micro-TEG), which is driven by the temperature difference between the process and the ambient surroundings. The device will be capable of running independently from the battery with a temperature difference of around 35°C.

The thermal harvesters are integrated into temperature transmitters and sold as an external option for pressure transmitters, without the need for any additional mechanical device for the connection or electronics circuitry for the power conversion and adaptation.

In addition, ABB is studying a smart power management platform that will accept external power sources and allow connection of different harvesters (vibration, solar, etc.) to power the devices. The platform will be extended

to other product lines like level and flow transmitters.

The devices will be released early in 2014, within the respective series: 266 Pressure, TTF300 and TSP3xx Temperature.

USB – and tea

Busch-Jaeger, a member of the ABB Group, has developed a SCHUKO® mains outlet with an integrated USB connector.

This award-winning product neatly solves the perennial problem of hunting for a USB charger and a cable and then, once found, deciding which domestic appliance should be unplugged to make way for it. With more and more domestic devices appearing that need to be recharged via a USB connector, the SCHUKO mains outlet with integrated USB connector will come as a relief to many consumers.

The flush-mounted outlet delivers up to 700 mA charging current and features child protection. Because the form factor matches existing SCHUKO outlets exactly, upgrading to the new USB socket is easy.

The company has developed two companion USB charging products for the SCHUKO USB outlet – a USB power supply and a USB charging station. The former provides two 700 mA (or one 1,400 mA) USB connectors for charging purposes; the latter features a nonslip device holder and charges via a micro-USB connector that can deliver up to 1,400 mA charging current – enough for even power-hungry tablets.

Several international prizes have been conferred on the SCHUKO USB outlet,

including the Audience Choice Award at the design pavilion of the 2013 IFA trade fair in Berlin.

For more information, please see the article “Smart outlets for smart phones” on page 55 in this issue of *ABB Review*.

Boosting wayside energy efficiency for DC trains

Rail vehicles regenerate braking energy through their traction motors (which work as generators). Most of the time, a small portion of this kinetic energy powers onboard loads, while the remaining energy is sent back to the network and reused if a nearby vehicle is accelerating. If this is not possible, the surplus is usually dissipated using onboard or wayside resistors. Thanks to ABB’s Enviline™ Energy Recovery System (ERS), this waste can now be avoided and overall energy consumption reduced by 10 to 30 percent – without the need to invest in new rolling stock or network control systems.

Enviline™ ERS consists of an IGBT inverter installed in parallel with existing diode rectifiers at the DC substation. It forces energy from the DC traction grid back to the AC grid. The ERS not only recovers energy from braking, it can also mitigate reactive power, provide active

filtering to reduce the effect of harmonics and support existing rectifiers.

Where selling back surplus energy is not an option, ABB offers the Enviline™ Energy Storage System (ESS). ESS is the industry’s smallest, most modular and flexible energy storage system and can be provided with supercapacitors for short duration storage, or with batteries to provide additional benefits and revenue generating services.

The benefits of the ESS include sustaining the voltage against sags, augmenting traction power during acceleration and reducing the penalties associated with high demand peaks. The ESS can also be used as a permanently installed or mobile standalone traction power system to replace conventional grid-connected traction power systems. When used with batteries, ESS can also provide emergency power and even generate revenues by participating in local energy markets, such as in ABB’s project with the South East Pennsylvania Transit Authority (SEPTA) in the United States.

ABB’s ERS won the electrification category award at Railtex 2013 in London.

For more information, please see the article “Braking news” on page 28 in this issue of *ABB Review* and also http://www.abb.com/railway

The lake that is a battery

One of the great strengths of hydropower is that energy is stored and can be released as and when required, making it ideal for meeting demand peaks. Pumped storage takes this concept one step further: Water can be pumped up the mountain, meaning both demand peaks and troughs can be mitigated. Pumped storage is playing an increased role in grid regulation and assuring the continuity of supply.

ABB has supplied the world's most powerful frequency converter for pumped storage to the Grimsel 2 plant of Kraftwerken Oberhasli AG (KWO) in Switzerland. This plant connects the upper reservoir of Lake Oberaar to the more than 400 m lower Lake Grimsel.

Until now, the pump operation could only be controlled by regulating the number of pumps in operation up to a maximum of four pumps. The 100 MW power-electronic frequency converter allows the speed of one of these pumps to be controlled according to the surplus energy available. The pump can now be started, operated and stopped more quickly, and water used more efficiently and flexibly for power production while also increasing the plant's contribution to grid stability.

Despite progress with other storage technologies, pumped storage remains the only mature and affordable means of energy storage suitable for grid regulation, and thus has an important role to play in the generation landscape of tomorrow. The new converter at Lake Grimsel is a contribution to the Swiss Energy Strategy for 2050, which seeks to assure the continuity of the Swiss energy supply while increasing the use of renewables.

The Grimsel frequency converter will be presented in greater detail in an upcoming issue of *ABB Review*.

Flash charging on the bus

Two major barriers to the adoption of electric vehicles are long charging times and the need to recharge frequently. Especially when it comes to public transport, the downtime associated with battery charging can be a major obstacle to the commercial viability of electric operation. Furthermore the size and weight of onboard batteries increases energy consumption and reduces space available to passengers. The TOSA bus, which is presently being demonstrated in the Swiss city of Geneva, presents an elegant response to this challenge.

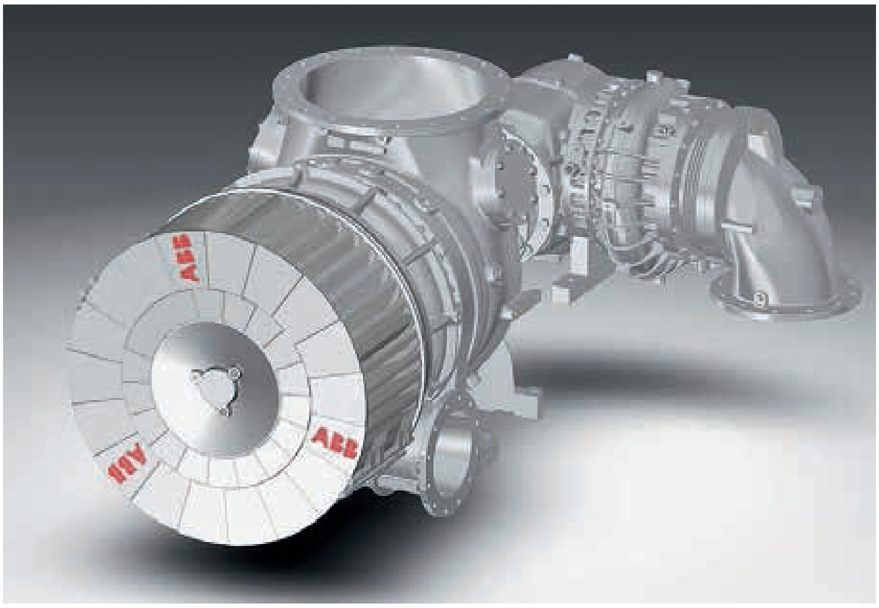
ABB's flash charging technology permits a bus to be recharged in only 15 s. Furthermore, this occurs at bus stops at which the bus needs to stop anyway, meaning schedules are not negatively affected. As soon as the bus has drawn to a halt, a contact on its roof automatically rises, using laser guidance to align with an overhead receptacle. A flash charger then delivers 400 kW for 15 s.

The energy delivered suffices as a top-up charge and helps reduce required battery capacity. Further brief recharging occurs as energy is recovered in braking. A longer and full recharge is provided at the bus terminus, where 200 kW can be delivered for 3 to 5 min using the same roof-mounted contact.

Because a 400 kW draw during flash charging can pose a challenge for the local electricity grid, the charger station uses super capacitors to flatten out the current peak and reduce the load on the grid. In contrast to solutions relying on recharging at night, TOSA is naturally suited to the use of solar power and its daytime availability.

For more information, please see the article "Taking charge: Flash charging is just the ticket for clean transportation" on page 64 of *ABB Review* 4/2013.

Power2 turbocharging gets a boost



Two-stage turbocharging is an important technology that offers reduced fuel consumption and emissions while enabling an increase in engine power density. With the Power2 800-M series, ABB introduces the second generation of two-stage turbocharging for large four-stroke diesel and gas engines.

The most important factors driving the development of modern four-stroke medium-speed engines are high total engine efficiencies, low operating costs and high power density while complying with ever-more stringent emissions legislation. ABB's second generation of Power2 presents a two-stage turbocharging system providing boost pressures up to 12 bar that enables engine designs to meet all of these targets.

All of Power2's parts have been optimized to meet the requirements for a two-stage system operating in marine, offshore and power-plant applications.

The new system features a new extractable cartridge with dedicated tools for easy removal and fast maintenance, along with new compressor and turbine stages optimized for combined operation in a two-stage system. The entire system has been reduced in size in order to minimize space requirements while still providing optimum performance.

Large industrial robots – the next generation

For over 30 years ABB has been developing large industrial robots to meet modern manufacturing needs. And now ABB has introduced a more robust robot than ever. The seventh generation of large industrial robots – the IRB 6700 – features a multitude of next-generation improvements derived from intimate customer relationships and exhaustive engineering studies.

The new generation robots show enhanced performance, reliability and significantly reduced cost of ownership. The IRB 6700 robots have higher payloads and longer reach and at the same time are faster, lighter and more accurate, with energy consumption reduced by 15 percent.

Every robot in the 6700 family is designed to accommodate Lean ID – an integrated dressing solution that places the most exposed parts of the dress pack into the robot. Equipping an IRB 6700 with Lean ID makes it easier to program and simulate with predictable cable movements, creates a more compact footprint, and lengthens service intervals due to less wear and tear.

In designing the new robot, easier serviceability was identified as a critical aspect for improving its total cost of ownership. Service routines for the machine have been shortened and intervals between them have been increased. Access to motors has also been improved. The first six robots in

the family, with payloads from 150 to 235 kg and reaches of 2.6 to 3.2 m, were introduced at the end of 2013. Two additional robot variants are being developed to meet the demands for payloads up to 300 kg, with a planned release by the end of 2014.

AC500-S Safety PLC speeds and simplifies safety engineering

The AC500-S Safety programmable logic controller (PLC) is a new addition to ABB's AC500 PLC product portfolio. It offers engineers flexible and powerful facilities that speed and simplify the development of safe control solutions for even the most complex control applications. It has already been used successfully in cranes, hoists, robots and wind turbines.

The AC500-S features a dual-processor architecture that complies with SIL3/PLe functional safety levels. It is programmed using Automation Builder, ABB's integrated engineering suite for AC500 PLCs, CP600 control panels, drives, motion control and robots.

The PLC has many new features appropriate to the safety machinery market, including support for high-level structured text (ST) programming, ladder logic and function block diagrams. The inclusion of ST programming support is a unique feature in the PLC world and it simplifies development when complex algorithms and mathematics are involved.

The AC500-S Safety PLC offers a choice of SIL3/PLe-certified Safety I/O modules including digital input and outputs, and a dedicated 0–20 mA (or 4–20 mA) analog input module.

To simplify system design and improve productivity, Safety I/O modules may be installed as part of the main PLC solution, or located in a remote I/O rack and linked using the PROFINET/PROFIsafe protocol.

The new AC500-S Safety PLC is perfectly integrated into the scalable AC500 PLC platform. This allows the customer to select the performance level appropriate to the target application and includes operation in harsh conditions and extreme climates.

SafeRing Air – a compact solution

ABB has developed a ring main unit (RMU) as compact as the traditional SF_6 insulated RMU but using dry air as an alternative, environmentally friendly, insulation gas, thus avoiding intensive use of epoxy materials.

SafeRing Air provides a solution using an insulating gas that consists of atmospheric components, without enlarging the physical dimensions of the product.

SafeRing Air is available for up to 12 kV in circuit breaker and load-break switch configurations for RMU applications that require alternative solutions.

The switchgear design is based on a completely sealed system with a stainless steel tank containing all live parts and switching functions. SafeRing Air is ideal for use in compact secondary substations, light industry, building and infrastructure applications. SafeRing Air has full three-way functionality with the same footprint as the current SafeRing with SF_6 insulation and is optimal for new installations and retrofit applications.

The switchgear design is based on the existing SafeRing/SafePlus portfolio, providing the same user interface, footprint, spare parts and operation in retrofits.

Digital switchgear

Innovative technologies have enabled the continued development of ABB switchgear for almost a century. UniGear Digital is the newest product available for medium-voltage air-insulated switchgear.

UniGear Digital combines the well-proven UniGear switchgear design with a unique solution for protection, control, measurement and digital communication. In the new design, state-of-the-art digital current and voltage sensors are integrated into each panel, alongside ABB's multifunctional Relion IEDs, which ensure compatibility with the IEC 61850 digital communication protocol.

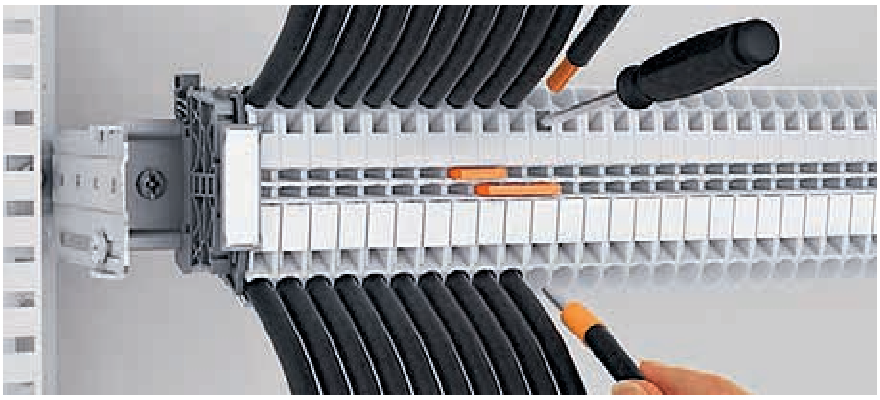
Packaging switching and communication functions together enables shorter delivery times by up to 30 percent, simpler installation, commissioning and testing, and energy savings of up to 150 t of CO_2 equivalent compared with a conventional UniGear ZS1 substation of 14 feeders with a 30-year lifetime.

Using IED connectivity packages makes connecting the digital switchgear to a customer's SCADA system simple and fast. New, high-performance applications such as high-speed busbar transfer and fast load shedding are enabled through the digital approach, thus enabling a higher performance level. UniGear Digital is built for flexibility and expansion without needing complex additional wiring.

The use of current and voltage sensors greatly enhance safety, as there is no risk for open current circuits, or for ferro resonance in the voltage transformers. The sensors also enable up to 30 percent shorter delivery time, due to variant standardization that eliminates the need for made-to-order instrument transformers. Deploying IEC 61850-9-2-based communication throughout the switchgear grants highly dependable protection and control functions.

UniGear Digital is currently available for ratings of up to 17.5 kV, 4,000 A and 50 kA. ABB plans to extend the digital concept to the entire 12 to 24 kV UniGear portfolio.

High-performance terminal blocks with screwless technology



Control cabinets are becoming a common sight in more and more industrial settings. Dozens of cables (thousands in larger installations) can run to such cabinets and each cable has to be properly terminated as just one faulty, connection can render the whole installation inoperable. ABB has now launched a new, patented PI-Spring terminal block, aimed at both standard and premium applications, to significantly increase connection reliability.

The PI-Spring terminal blocks allow push-in connection for rigid, or flexible, ferruled conductors; nonferruled flexible conductors can be connected by operating the block spring with a screwdriver during insertion. Cable connection is now 50 percent faster than with standard technologies.

The PI-Spring connectors are resistant to vibration, shock and aggressive atmospheres, and global certifications give access to worldwide markets and many industrial applications, including hazardous environments and marine duties.

As the push-in and spring modes are both provided by one single stock profile, inventory can be reduced by 50 percent. In addition, the PI-Spring range shares the same accessories as ABB's SNK screw terminal range and all PI-Spring end sections fit many blocks, further reducing logistical effort.

The asymmetrical block design allows an immediate visual check for reversed terminal blocks. Quick premarking with a pen before final labeling is facilitated by the large, flat marking surface, and the 30° angle of the conductor entry saves up to 15 percent in height while still allowing for a generous bend radius.

ABB's PI-Spring terminal blocks will be presented in more detail in an upcoming edition of *ABB Review*.

Light measures current

A fiber-optic current sensor integrated into a high-voltage circuit breaker

KLAUS BOHNERT, RICHARD THOMAS, MICHAEL MENDIK – Current and voltage measurements are two key functions in the control and protection of electric power grids. Traditionally, they have been performed using so-called instrument transformers – somewhat bulky and heavy devices that can weigh up to several tons. It has long been recognized that fiber-optic-based devices that exploit the Faraday effect have great potential as an attractive new technology for current measurement. The remarkable progress made in optical telecommunications over the last 20 years has delivered components such as light sources, optical fibers, modulators and photodetectors that can be reused to produce fiber-optic current sensors (FOCSs) that are reliable and commercially attractive. Moreover, FOCSs have also benefited from the rapid development in recent years of fiber-optic gyroscopes, which use techniques that exploit the same basic physical effects.

Title picture
For many decades, current measurement in high-voltage equipment has relied on bulky transformers that could weigh up to several tons. These will now be replaced by ABB's fiber-optic current sensor, whose small size allows it to be integrated into primary equipment such as circuit breakers.

Over 40 years ago it was recognized that the Faraday effect in optical fibers could be the basis of a new, and better, technology for current measurement.

1 Fiber-optic current sensor for large DC values

Presently, currents in high-voltage equipment are measured using bulky and heavy current transformers (CTs). These use the principle of electromagnetic induction to generate a small secondary current, typically 1 A or 5 A at rated current, from a primary current, which then serves as an input for protection relays or energy meters. Such transformers have represented the state of the art for many decades and they operate reliably under the harsh conditions found in an outdoor substation. However, besides their size and weight, they have a number of additional shortcomings – the most important of which is that, as a result of magnetic saturation and limited bandwidth, the waveform of the secondary current is often not a true image of the primary current.

Over 40 years ago it was recognized that the Faraday effect in optical fibers could be the basis of a new, and better, technology for current measurement. But it is only in the last 20 years that appropriate technology has become sufficiently mature to allow it to be used as a commercially attractive basis for FOCS applications. The remarkable progress made by the optical communications business has provided many components that can be reused for the FOCS – such as light sources, fiber-optics, modulators and photodetectors.

FOCS has also benefited from the development of fiber-optic gyroscopes. Today, fiber gyros are in use in numerous navigation systems – in the aerospace industry, for example. These gyros use techniques similar to those employed by the FOCS to measure the differential phase shift of light waves. Whereas in gyroscopes the phase shift is the result of a rotation (the Sagnac effect), in optical current sensors it is caused by the magnetic field of the current to be measured.

FOCS history

In 2005, ABB introduced a high-performance fiber-optic current sensor for the measurement of DC up to 600 kA, particularly for use in the electrowinning of metals [1,2] → 1. The sensor accuracy is within 0.1 percent over a range from 1 percent to 120 percent of the rated current and in temperatures from −40 to +80 °C. The sensor is now in use worldwide – in aluminum smelters, copper electrowinning facilities, chlorine plants and even nuclear fusion research installations.

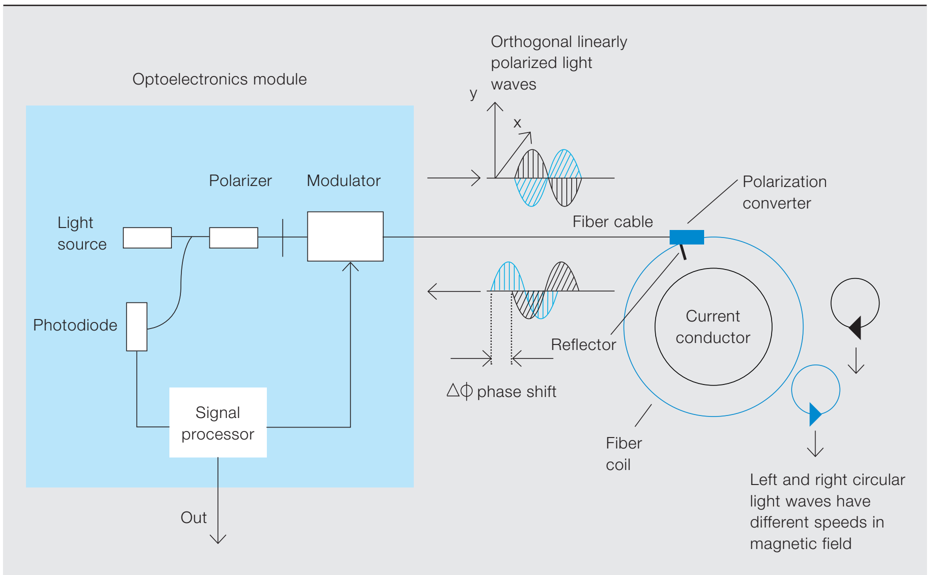
Recently, ABB has developed the sensor further with a view to implementing it in high-voltage substations. Because of its small size and flexible form factor, an optical current sensor does not need to be a standalone device like a traditional instrument transformer. Instead, it can be integrated into primary high-voltage equipment such as circuit breakers – this results in substantial savings in space and installation costs. Another important aspect of the new technology is its ability to communicate digitally, via an optical process bus, with control and protection devices. The process bus replaces large numbers of copper cables and provides more flexibility in the configuration of a substation.

How it works

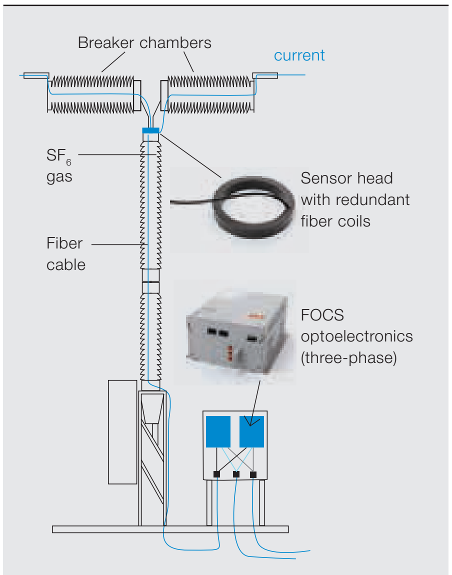
The FOCS exploits the Faraday effect. The Faraday effect is caused by the fact that left and right circularly polarized waves propagate at slightly different speeds when they travel in a medium that is subject to a magnetic field. To exploit the effect, a linearly polarized wave is decomposed into two such circularly polarized components that are then coupled into an optical fiber that is exposed to a magnetic field (caused, in the case discussed here, by the current to be measured). The effect of the relative phase shift between the two components caused by the Faraday-effect-induced speed difference is to rotate the orientation of the wave's linear polarization. This can be used to deduce the magnitude of the current.

The main components of the FOCS are an optoelectronics (OE) module at ground potential and a coil of sensing fiber, which is wound around the current conductor → 2. The OE module includes a semiconductor light source and a closed-loop detection circuit with a fiber-optic polarizer, an optical phase modulator and a digital signal processor. The module sends two

2 Fiber-optic current sensor



3 FOCS integration in live tank breaker



light waves with orthogonal linear polarization to the sensing fiber coil. At the coil entrance a fiber-optic polarization converter transforms the linear waves into left and right circularly polarized light waves. These waves travel at different speeds through the sensing fiber in the magnetic field (caused by the current) as a result of the Faraday effect, as explained above, and this in turn creates an optical phase difference. The waves are reflected at the end of the fiber and they retrace their optical path back to the optoelectronics module where they interfere at the polarizer. The signal that results from the interference depends on the phase difference and is measured by a photodiode. The closed-loop control circuit reverses the current-induced phase shift by means of a phase modulator so that the phase difference of the waves when they interfere at the polarizer is always kept at zero. The feedback signal to the modulator is then essentially an image of the primary current and the digital sensor output is derived from this signal. A particular advantage of this closed-loop detection scheme is that the signal is perfectly in proportion to the primary current over the entire measurement range.

The roundtrip phase difference of the two light waves is proportional to the number of fiber loops and the line integral of the magnetic field along the closed path described by the sensing fiber. Geometrical parameters such as the coil diameter or the position of the conductor inside the fiber coil do not affect the signal. Currents outside the coil have no influence.

Operation of the sensing fiber in reflection mode has the advantage that the sensor becomes immune to mechanical disturbances. The mirrored coil end swaps the polarization states of the light waves. As a result, vibration-induced phase shifts cancel each other out over one roundtrip of the waves while the non-reciprocal magneto-optic phase shifts double. The basic concept of the sensor was invented at ABB in 1992 and has been adopted by others.

By appropriately selecting the number of fiber loops, the measurement range can be optimized for specific applications. The sensor described here has a range of ±180 kA. The operating temperature range of the sensor head is from below −40 °C to 105 °C. The OE module is designed for operation in a heated outdoor cubicle. It can be operated with three fiber coils to cover all three phases normally found in a high-voltage installation.

FOCS benefits

Particular benefits of the FOCS are:

High accuracy

Within the bandwidth determined by the output data rate, the sensor delivers a true image of the primary current waveform that is not affected by magnetic saturation or remanence. The DC contents of a current are correctly recorded. The sensor targets both protection and metering applications.

> The remarkable progress made by the optical communications business has provided many components that can be reused for the FOCS, such as light sources, fiber-optics, modulators and photodetectors.

4 Three-phase FOCS system (redundant)

5 REL670 relay with IEC61850-9-2 communication

FOCS has also benefited from the development of fiber-optic gyroscopes.

Reduced environmental impact

The FOCS saves the aluminum, copper, insulation materials and transformer oil that constitute a corresponding conventional CT. A 550kV CT, for example, can have a weight of about 3.5 tons, which may include 500kg of oil.

Zero footprint capability

The sensor need not be a standalone device but may be integrated into other power products such as circuit breakers or bushings ➔ 3.

Safety of operation

Risks of catastrophic failure, eg, during earthquakes, or safety issues due to an open secondary circuit, are excluded. The electronics are galvanically separated from high voltages.

Digital communication

A fiber-optic IEC 61850-9-2LE process bus connects the FOCS to bay-level control and protection devices and replaces large amounts of copper cable – as much as tens of kilometers per substation. It also provides more flexibility in the configuration or later reconfiguration of a substation. The communication data rate is 4 or 4.8kHz at line frequencies of 50 or 60Hz, respectively. Higher data rates (eg, up to 100kHz), that may be of interest in other applications are possible with alternative interface options.

FOCS in live tank breakers

The small and easily adaptable size of a current sensor fiber coil makes it possible to integrate the sensor into other power products. For example, a redundant three-phase FOCS system can be integrated into an ABB double-chamber circuit breaker such as the 550kV HPL550B2 ➔ 3 – 4. Each of the three ring-shaped sensor head housings shown in the figure contains two fiber coils and is mounted at the upper end of the corresponding breaker pole. The current path is modified in such a way that the current flows through the coils as indicated. The two fiber-leads to the coils are in a special protective cable that is suited for the live tank breaker (LTB) gas atmosphere. The cable runs to ground through the gas volume and leaves the breaker pole through a gastight feedthrough. The two three-phase OE modules are mounted in a cubicle near the breaker or are attached to the breaker support frame. Redundant IEC 61850-9-2LE links connect the sensors to protection relays such as ABB's REL670 in the control housing ➔ 5.The solution has many benefits:

- In-factory installation: The integration of the sensor heads into the LTB and the OE modules into their cubicle is done in the factory. The only remaining installation work to be done in the field is to set up the cubicle for the OE modules and deploy the fiber cables.
- The sensor head is part of the LTB pole and does not interfere with the LTB assembly in the field. In fact, only minor changes in the LTB assembly procedures are needed.
- There is no need for an extra insulator to bring the fiber from high voltage to ground.
- Zero footprint: The space required for a conventional CT or standalone optical CT is eliminated. This reduces the substation size and saves real-estate costs, particularly when the sensors are combined with disconnecting circuit breakers [3].
- The CT foundation and support structures are no longer needed.
- The outdoor placement of the opto-electronics modules near the LTB minimizes the length of sensor fiber cable required.
- The transmission of digital optical signals from the sensor electronics to the substation control function via the redundant IEC 61850-9-2LE links is immune to disturbance.

The design of the LTB with an integrated FOCS was verified to be in compliance with the relevant type tests as defined by IEC standards. The tests included high-voltage tests, T100 tests (ie, verification of breaker operation at high current and voltage), temperature-rise tests (temperature rise at a current of 4,000 A_{rms}) as well as mechanical endurance tests consisting of over 10,000 breaker open-and-close operations. Proper sensor operation be-

6 Live tank breakers, 420 kV, with integrated FOCS

7 LTB with integrated FOCS

fore, during and after the tests was verified. Other tests ascertained the electromagnetic immunity of the sensor.

Ascertaining reliability

The FOCS technology has already been proven in the harsh environments of the electrowinning industry over a period of several years. However, the demands on reliability in high-voltage substations are even more stringent – for example, no particular maintenance or recalibration should be necessary during a lifetime in the field. Therefore, the reliability of the FOCS and its components is being verified by accelerated aging and long-term performance tests in-house. Self-diagnostic functions continuously monitor the operation of the sensor. Furthermore, precommercial field installations serve to gather experience of installation and commissioning of the new technology and to prove its reliability under substation conditions.

Technology pilot

A FOCS pilot installation has been set up in collaboration with Svenska Kraftnät (Swedish National Grid) at a 420 kV substation ➔ 6–7. The installation consists of a three-phase LTB with a redundant three-phase FOCS system. The two OE units are mounted in the phase B breaker drive cubicle. Two IEC 61850-9-2 links connect the OE units to two ABB REL670 digital relays in the control housing. A CT with protection and metering cores serves as a reference. A pulse-per-second source synchronizes the system. Data is recorded at regular intervals for long-term comparison. Furthermore, the protection function can request disturbance recordings to be made. Besides verifying the performance and reliability of the sensor under field conditions, the pilot has also served to verify the assembly procedures in the factory, and the installation and commissioning in the field.

The system has been in incident-free operation since April 2010. Performance has been within specifications. Moreover, the superiority of a FOCS over a conventional CT in the recording of transient fault currents has become obvious. This may lead to the development of more efficient protection and control functions in the future.

Looking ahead

The FOCS technology will serve as a platform for other high-voltage applications. The variable diameter of the sensing head allows the sensor to be easily adapted to high-voltage equipment such as gas-insulated switchgear (GIS) or generator circuit breakers. By choosing the fiber loop number appropriately, high accuracy can also be achieved at low currents, eg, in zero sequence current measurements. New or improved substation protection and monitoring functions may follow from the fast response of the FOCS and its precise measurement of both AC and transient DC.

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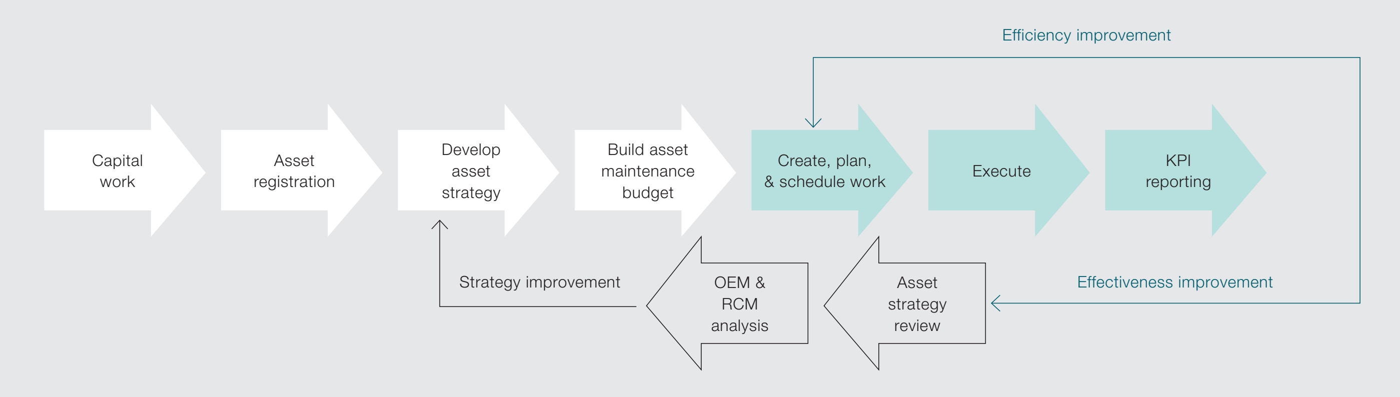
Picture of health

An integrated approach to asset health management

KAREN SMILEY, SHAKEEL MAHATE, PAUL WOOD, PAUL BOWER, MARTIN NAEDELE – Asset-intensive industries face increasing pressure to improve how well they utilize and maintain their equipment. Asset health management is emerging as a critical business process due to the potentially very significant bottom-line impact of asset decisions on profitability, compliance and customer satisfaction. To guide better-informed decisions and eliminate wasteful expenses, ABB's Asset Health Center (AHC) blends business intelligence and asset analytics, incorporating expert knowledge of industrial equipment and verticals. ABB is now leveraging its expertise in power transmission to help a large North American utility optimize capital expenditures, and operations and maintenance plans. A new Subject Matter Expert (SME) Workbench will further expand these analytics and extend asset health management capabilities to other areas.

1 The asset management life cycle



An asset is a physical, capital-intensive resource with a life cycle and, unavoidably, costs → 1. In asset-intensive industries, managing assets well is critical to business success. Due to increasing concerns such as aging infrastructure, financial pressures, regulatory concerns and loss of workforce skills through retirement, traditional asset maintenance strategies relying solely on reactive-based or schedule-based actions no longer meet the business objectives of many of ABB's industrial customers. Asset decisions generally affect many business processes, so decision makers must consider multiple planning horizons and must trade off one set of objectives against another. Knowledge-based asset analytics can characterize the effect of various decision alternatives in terms of their impact on the enterprise performance indicators that matter.

However, asset knowledge is often spread throughout an organization and among its service providers, and may be "stored" on engineers' desks, laptops and desktops in word-processing documents, spreadsheets, flowchart diagrams, etc. Capturing this knowledge and making it usable in enterprise asset analytics is a key challenge.

Multiple sources of asset data

Asset analytics can combine traditional asset health records with operational performance data, asset registry metadata and data from sensors, tests and inspections. As systems grow more complex and numerous, these data volumes become greater. Asset health data may be trapped, unutilized in conventional offline or paper records, or live data streams from smart assets may be lost due to poor storage. Often, data is stored in databases from different vendors and these systems may even use different ways to uniquely identify the same asset.

These data and analysis challenges are solvable by combining careful thought, instrumentation, data interchange and innovation. In some regions of the world, utilities are vigorously driving the deployment of asset health sensors in their equipment to increase visibility into asset performance. However, data processing and analytics that exploit the data a customer already has can jump-start asset health management. For instance, islanded data can be imported or asset data can be extracted by scanning and processing offline records.

Acting on asset data

Apart from the challenge of collecting and integrating all the available asset data, there is also the challenge of knowing what then is to be done for each asset throughout its life cycle. Asset analytics that leverage subject matter expertise enable businesses to capitalize on predictive, condition-based maintenance strategies. Corrective maintenance may, in some cases, be the best choice, but without the right tools in place, and integrated with each other, businesses cannot make the most effective asset decisions. To achieve optimal results, customers need actionable insights into how their asset operations and maintenance decisions and plans might impact their objectives over time. The ABB Asset Health Center (AHC) is designed to surmount the challenges in providing those critical insights.

> Asset analytics can characterize the effect of various decision alternatives in terms of their impact on the enterprise performance indicators that matter.

Asset Health Center

The AHC's goal is to capture and aggregate data, draw insights and provide decision support in order to achieve a broad range of economic and noneconomic benefits → 2. AHC is based on ABB's FocalPoint business intelligence (BI) platform.

Title picture
ABB's Asset Health Center provides customers with the actionable insights they need to make and execute decisions on asset operations and maintenance that are optimal for their businesses.

To achieve optimal results, customers need actionable insights into how their asset operations and maintenance decisions and plans might impact their objectives over time.

2 Asset integration drivers (GTM Research, 2013) [1]

Type of driver	Driver	Reason
Economic	Reliability	Reduce exposure to regulatory penalties
		Reduce unplanned service disruptions
		Reduce the impact of changing workforce demographics
		Extend asset life and reduce downtime
	Workforce efficiency	Support decision-making for maintenance prioritization
		Improve scheduling of maintenance crews
		Automation of analysis process reduces labor cost
	Risk management	Reduce exposure to catastrophic failures and their collateral damage
	Optimize asset utilization	Improve awareness of asset condition to enable dynamic stressing
Noneconomic	Executing compliance and reporting	Reduce time required to create reports on performance
		Formalize asset evaluation, monitoring and procurement processes
	Networking infrastructure	Reductions in the cost of communications and technological advancements have made communicating with remote, isolated sensors far cheaper and more readily available.
	Data acquisition and processing power	Increases in the number of digital monitoring and control devices in the industrial and utility industries are creating a prodigious stream of data that can be processed at a fraction of the cost due to distributed computing and the drastic reduction in hardware costs.
	Increased enterprise integration	Operational silos continue to converge as integration between various systems and groups within asset-intensive corporations continues to increase as these organizations attempt to leverage data from across the enterprise to gain efficiencies.

The FocalPoint platform has always provided customers with industry-specific data analysis and visualization so it forms a good foundation to deliver asset analytics to the asset-intensive industries ABB serves. Using the platform's capabilities to integrate data from multiple, disparate systems provides a comprehensive view of each asset. In particular, bringing together data from traditional IT systems (such as an enterprise asset management program or a mobile inspection tool) and systems such as SCADA or a specialized sensor network, and analyzing this data in a holistic manner, will unlock new possibilities for assessing risk and supporting decisions on asset maintenance or replacements.

In asset-intensive industries, managing assets well is critical to business success.

The AHC combines IT/OT (operational technology) integration and analytics with dashboards, such as in the asset monitor ➔ 3, and domain-relevant visualizations to provide insights to planners, decision makers and executives.

Benefits of the AHC

The four components of the AHC complement each other ➔ 4. Asset master data, and asset performance and condition data, are provided as input to the analyses; outputs of condition diagnosis, recommendations and criticality are visualized; based on the results from asset decision support analyses, decisions are made and service actions are triggered; and the service actions lead to updated asset information.

Within its analytics fabric, the AHC executes the asset-specific diagnosis, criticality and optimization modules. The algorithms that form the core of these modules were developed by ABB's experts in transformers and circuit breakers in power transmission and distribution grids.

3 The AHC asset monitor provides easy-to-interpret insights into risk and consequence of failure across an asset portfolio, such as this fleet of transformers.

Asset health analysis data can be leveraged throughout the enterprise. Indeed, a comprehensive approach to better asset management complements generic BI toolkits by exploiting the knowledge of such asset and domain experts.

Leveraging asset expertise in analytics

Subject matter experts (SMEs) understand how a complex system is put together, its characteristics and tradeoffs, the key engineering design decisions, the environments in which the asset may operate and how maintenance updates or events can impact the health of an asset or system. SME knowledge is leveraged in many types of industry-relevant asset analytics, for instance:

- Asset condition: Asset performance models characterize the health or condition of assets. This includes quantifying the likelihood of failure or degraded performance, identifying likely causes of particular conditions and recommending improvement actions.
- Asset importance: Asset criticality models describe the importance of the asset by characterizing the impact of changes in asset condition on the performance of the industrial enterprise. This includes impact on operations, impact of restoration activities and interdependencies with other assets.
- Asset decision support: Asset decision support analyses combine knowledge and data to deliver effective guidance on asset-related decisions.

As an example, a useful decision support analysis for a regional power transmission company may consider total risk of failure – combining health and criticality information – to determine the optimal overall capital expenditure budgets and operations and maintenance plans for each of the next two years.

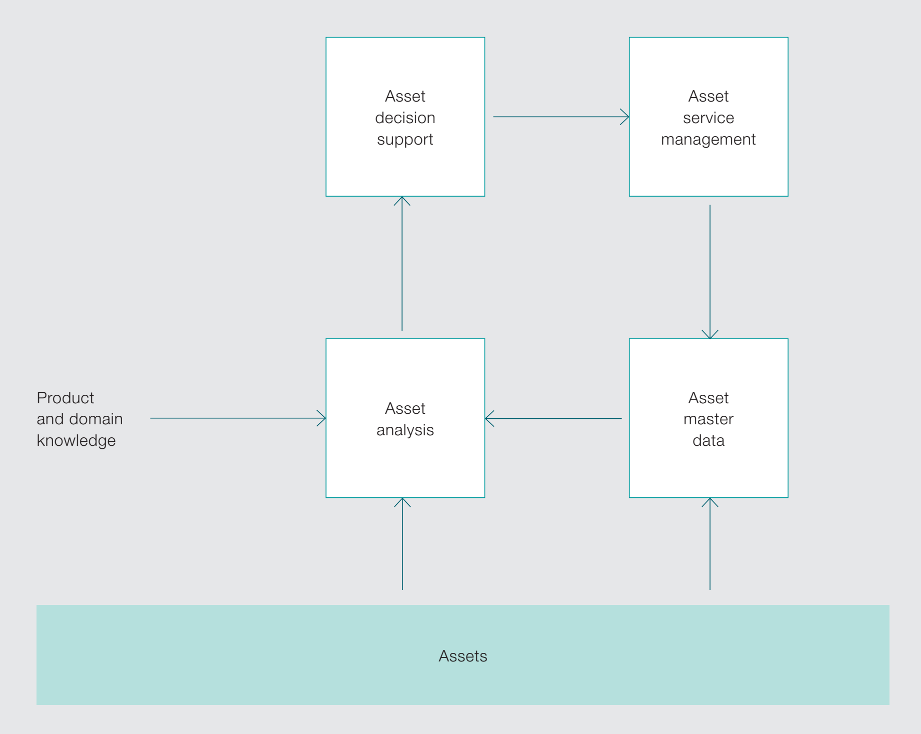
Speeding up creation of analytics by asset experts

Making it as easy as possible for asset experts to convert their asset and domain knowledge into executable software system modules is crucial. Three actions are key to this:

- Embed ABB expert knowledge in the software for the wide variety of equipment and systems that ABB provides.

The SME Workbench supports asset analytics across multiple industrial verticals with a common development tool and enables asset, data and performance experts to focus on what they know best.

4 The ABB Asset Health Center integrates all components needed for comprehensive asset management.



– Capture customer asset performance models to complement the ABB subject matter expertise ("end-user programming").
– Enable third parties (eg, other vendors or expert consultants) to contribute complex asset diagnosis modules via an application programming interface (API).

The SME Workbench was created to meet these three requirements and satisfy this goal. It supports asset analytics across multiple industrial sectors with a common development tool and enables asset, data and performance experts to focus on what they know best.

Freeing asset experts to focus on knowledge

The SME Workbench enables the asset expert to build algorithms without the need to know how data is fetched or stored and frees them from understanding how the algorithms will execute in an enterprise environment. Asset SMEs can now naturally describe their expertise using visual editors such as flowcharts, decision trees and other familiar tools.

As a team of SMEs collaborates to build an asset performance model, the artifacts of the model are stored in a cloud repository, while the SME Workbench provides infrastructure to test the analytic model locally.

Benefits of the SME Workbench

The SME Workbench enables anyone with asset expertise to quickly develop new analytic model plugins. The visual drag-and-drop interface helps asset experts to quickly convert their ideas and algorithms into high-performance software modules. Customized toolboxes provide SMEs with easy access to the calculations and reliability analysis functions that are most relevant for asset analytics. In addition to enabling SMEs to efficiently share their knowledge, the SME Workbench can be extended with new editors tailored to streamline development of asset analytics for different domains.

The SME Workbench and APIs allow customers and third parties, including non-ABB asset vendors, to contribute analytics that can be seamlessly integrated into the AHC analytics structure. This approach allows the capture and dissemination of knowledge that can be spread throughout the organization.

Reuse and extensions to new domains

The initial ABB AHC customers are power utilities, so the first asset diagnosis analytics have been oriented toward

Bringing data together from traditional IT systems and OT systems such as a SCADA, and analyzing it in a holistic manner, will unlock new possibilities for assessing risk and supporting decisions on asset maintenance or replacements.

power grid equipment. A benefit of the AHC architecture is that the BI platform and SME Workbench are domain-independent. ABB has strong domain knowledge in many asset-intensive industry verticals, such as oil and gas, water, mining and marine. This asset health offering will be extended to these other industries as ABB's asset and domain experts use the SME Workbench to contribute their knowledge.

The Internet of smart assets

ABB's vision for the future of asset health management is based on a system that integrates information about the asset with diagnostic expertise, presentation of actionable information and support for executing those actions. ABB can, for this purpose, integrate asset diagnostics and analytics developed by experts with its portfolio of powerful and proven applications that cover:

- Enterprise asset management in capital-intensive industries
- Asset information visualization and drill-down
- Service crew scheduling and task support

Analytics, dashboards, visualizations and the ability to ask questions and get meaningful answers are all necessary, but not sufficient. Assets with health sensors and networking capabilities will become more and more common, while asset designs and knowledge will continue to evolve. The AHC supports a closed-loop solution that can predict asset performance and that can help optimize operation and maintenance, expenses and capital investments. The AHC drives asset performance and optimizes business results by continuously capturing information from an array of smart assets, systems and sensors, which the advanced analytics engine processes to extract actionable insight.

Asset health management is emerging as an increasingly critical business process because it impacts the bottom line of customers. ABB is moving forward with an integrated AHC that combines business intelligence and analytics. By using the SME Workbench to facilitate analytics development and integration, expertise can be captured and applied to provide better decision guidance to asset-intensive industries. ABB is now fulfilling a contract to deliver this AHC solution to the largest transmission equipment owner in North America. By streamlining capture and use of subject matter expertise, more knowledge can be leveraged to further enhance the analytics and to apply the solution to other verticals.

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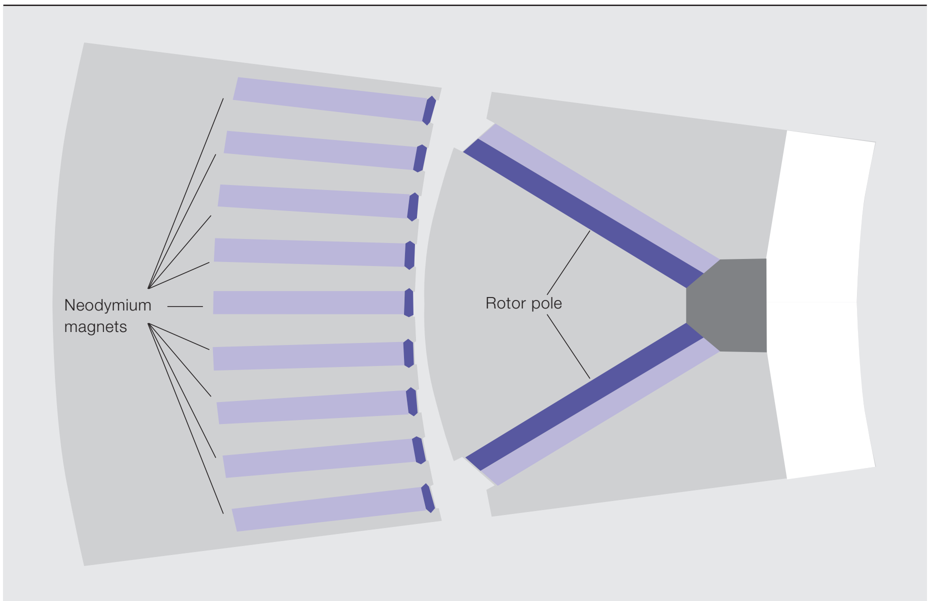
Wind of change

Design and test of a 7 MW wind turbine drivetrain

ERKO LEPA, TOBIAS THURNHERR, ALEXANDER FAULSTICH – Wind turbines are being installed at record rates around the world. With the vast capital sums being spent on this type of equipment, it is essential that the best technology is chosen. The market for wind turbine powertrains has, until now, largely been dominated by doubly-fed induction generators, but the market share of full-convertor-based concepts is increasing. Of these, it can be shown that the medium-voltage (MV), medium-speed class provide the best characteristics for utility-level applications: MV systems provide a low-current solution that minimizes cable losses, makes generator design easier and allows the use of a robust MV converter with high availability; medium speed allows a solution that is compact, lightweight and of the highest efficiency, compared with all other concepts. It pays dividends to design the components of a wind turbine carefully and this is illustrated here by the design and integration test of a 7 MW unit.

1 Rotor geometry



The doubly-fed and full converter electrical drivetrain concepts are the two prevalent in today's utility-scale wind turbines. The primary differences between them are the type and size of generator used and the function of the converter. The market has largely been dominated by the doubly-fed induction generator, but full converter concepts are now increasing their market share. There are several factors driving this shift, including grid code compliance and optimized power generation at lower wind speeds.

In the full converter concept, the converter decouples the generator and the mechanical drivetrain from the grid and all the generated power flows through the converter to the grid. The converter provides the generator's torque and speed control.

There are three types of full converter concept, each using different gearbox and generator solutions: low-speed (also known as direct drive), medium-speed and high-speed. In these, permanent magnet synchronous generators (PMSGs) and squirrel cage induction generators (SCIGs) are typically used.

Low-speed full converter type

The low-speed full converter (LSFC) type, also known as the gearless direct drive concept, uses a large diameter, low-speed (up to 30 rpm) generator. Permanent magnet or separately excited synchronous generators with a single bearing are typically used.

Medium-speed full converter type

In the medium-speed full converter (MSFC) type, either a single-stage or two-stage gearbox is used with a compact medium-speed permanent magnet generator (MS PMG). The nominal speed of the generator varies between 100 and 500 rpm. This concept causes less mechanical stress due to the lower speed and integrated gearbox solution. The integrated gearbox also results in a compact overall size.

High-speed full converter type

The high-speed full converter (HSFC) type runs at around 1,000 to 2,000 rpm, is mechanically similar to the doubly-fed induction machine and uses a normal three-stage gearbox. The overall size is small.

The main advantages are lower weight and smaller generator size.

Selecting a drivetrain

As each drivetrain type will result in different turbine weights, sizes and maintenance needs, selecting an appropriate drivetrain requires care and must take into consideration all of the turbine requirements, certification needed and grid code specifications.

Choice of voltage

The chosen speed concept does not determine the system voltage. Instead, the voltage is chosen based on the power level required. As a rough guide, for generators up to 3 MW, a low voltage is chosen (eg, 690 V). Above this, it often makes sense to choose a medium voltage (eg, 3.3 kV). This is mainly done to reduce the converter current. Lower current means the losses in the cables are lower. Additionally, design and part sourcing is simplified.

Choice of generator speed

The choice of rotation speed depends on the particular characteristics of the drive components – eg, gearbox, generator, converter and transformer.

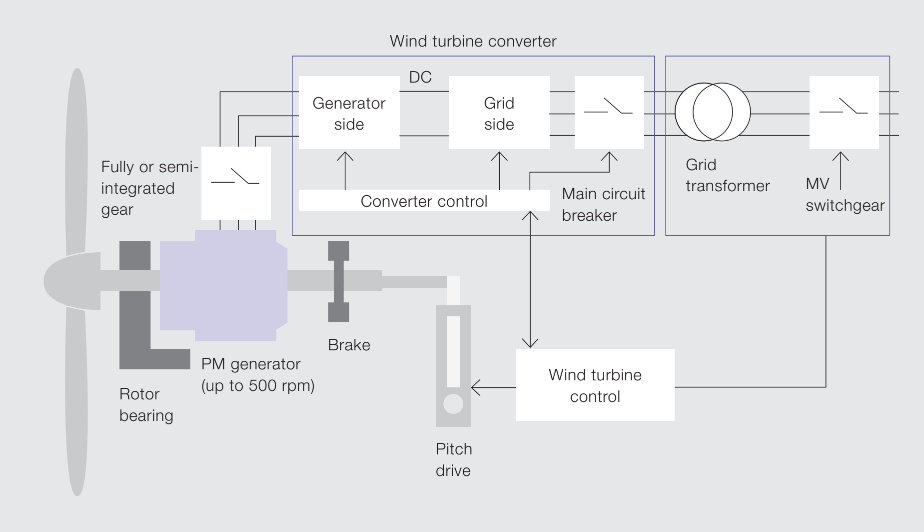
Direct investment perspective

Depending on the design, turbine power, grid requirements and market prices of the materials, the high-speed concept usually has the lowest direct investment costs. Direct drives are normally the most expensive solution, with medium-speed being slightly more expensive than high-speed solutions. However, maintenance costs, availability and annual wind distribution also contribute to lifetime costs, so only an analysis of all aspects can determine which concept delivers the most benefit.

Title picture

Choosing the right system components, such as this water-cooled, medium-speed permanent magnet generator, can bring huge benefits over the lifetime of a wind turbine. What are the critical design aspects involved?

2 ABB PCS 6000 converter schematic



3 Possible converter arrangements

Medium-speed PMSGs deliver over 98 percent efficiency – the highest of any commercial wind generator design.

Efficiency of different concepts

Calculations show that the medium-speed concept with a PMSG delivers the highest efficiency at the nominal point. In fact, medium-speed PMSGs deliver over 98 percent efficiency – the highest of any commercial wind generator design. Efficiency is also high at partial loads in low wind conditions and this enables the highest annual production of kWh. In addition, gearboxes can be smoothly integrated for a compact solution and the lower rotation speed means less wear in drivetrain components.

Choice of generator type

The power factor of an induction generator (IG) decreases as the number of poles increases and the pole pitch decreases. IGs are, therefore, competitive with synchronous generators (SGs) when their number of poles is small – ie, IGs are strongly competitive in high-speed applications. In medium-speed applications, IG efficiency is significantly lower. Generally, the greater the diameter of the generator, the higher its performance will be. As SGs can have a greater number of poles, the air gap diameter can be increased and there is greater flexibility in dimensioning the nominal frequency.

For low-speed, the only options are the PMSG or high-speed electrically excited synchronous generator (EESG). Both provide superior efficiency up to wind speeds of 8 m/s – ie, roughly 0 to 40 percent of the turbine nominal power. Above that, other concepts compete strongly.

With PMSGs the rotor is lighter, the generator efficiency is higher and the machine size is smaller, as there is no excitation system. Thus, PMSGs offer the best technical advantages in direct drive (DD) concepts.

Design of a medium-speed PMSG

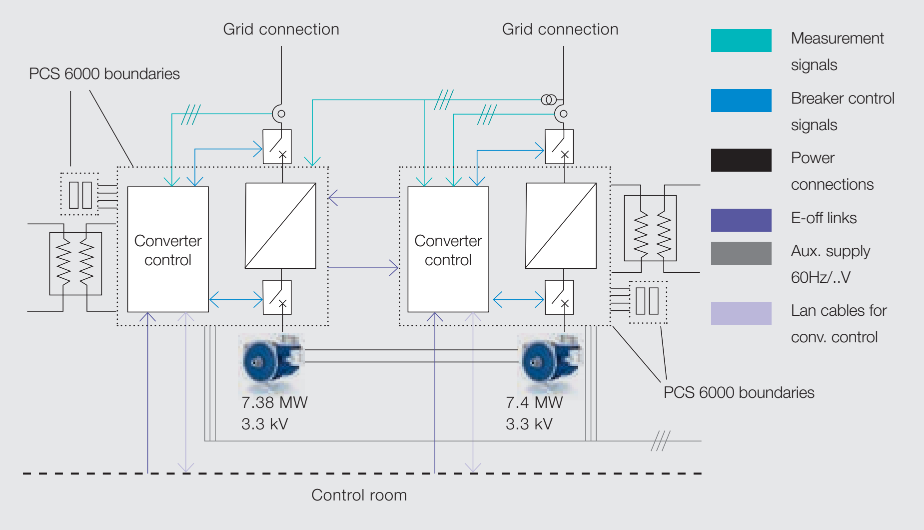
A 7 MW medium-speed PMSG and converter were designed and tested. Several design aspects are important:

- Due to the long distance from the generator to the transformer and high turbine power, a PMSG with an MV converter was selected.
- Calculations showed that 14- to 20-pole solutions were feasible from the performance and manufacturability points of view. Designs with 16 and 18 poles were quite similar, with negligible differences in losses, power factor, back-emf and active material masses. The inductances and load angle were slightly smaller in the 18-pole design, which was, consequently, chosen.
- After comprehensive calculations, optimizations and analyses, a V-type rotor pole shape was designed ➔ 1. Neodymium magnets with a high intrinsic coercivity force were chosen, based on simulations of sudden load and short-circuit conditions with different magnet properties and temperatures.
- In the design phase, it is important to identify potentially harmful resonance frequencies in the mechanical structure and provide enough damping and stiffness to tolerate the forces involved. It is equally important that the converter modulation strategy and switching frequency are adjustable. Based on experience, a change of about 50 Hz in the switching frequency will shift the excitation frequency from the resonant point and might lower the noise and vibration level significantly.

Converter design

The converter used for the 7 MW wind turbine electric drivetrain is based on a MV integrated gate-commutated thyristor (IGCT) with a three-level neutral-point

4 Back-to-back setup



clamped (NPC) topology. The IGCT combines the low conducting losses and reliability of a thyristor with full switch-off capability. The nominal converter voltage of 3.3 kV used not only means that the cabling effort and cable losses can be reduced compared with a converter with a lower output voltage, but also that fewer semiconductors are used, reducing failure points. The modular design of the ABB PCS 6000 product family converter allows a tailored mechanical arrangement of the converter components, whether the converter is placed in the tower, nacelle or a separate container outside the turbine, with different possible arrangements ➔ 2–3.

Integration tests

For the integration test, two generators were mechanically coupled and both were connected to the grid through a frequency converter ➔ 4. One PCS 6000 drove the connected generator as a motor, or so-called prime mover. This drove the other generator, which generated power back to the grid through the other converter. With this test setup, only the losses of the whole system have to be covered from the grid. The setup allows the generator to be run at nominal power, provided that the driving converter is able to operate with nominal turbine power and can cover the total losses in the setup.

The generator temperature rise was as calculated and converter component final temperatures remained under the component limits. The generator no-load voltage was lower than calculated and this reduced the power factor of the generator. Despite this, the generator main ratings were as calculated. The three-phase short circuit test after temperature rise demonstrated that the generator magnets were protected against demagnetization, as designed. The generator vibrations and emitted noise were measured and the values were well below the IEC criteria. The efficiency of the generator was 98.17 percent at the nominal point and exceeded expectations at other loading points.

Lower current means lower losses in the cables and simpler design and part sourcing.

Different switching frequencies over the whole speed range in different modulation modes were tested. The best results were achieved with a fixed pulse width modulation carrier frequency of 720 Hz or above over the whole speed range, in asynchronous mode. Asynchronous mode provided favorable results because the switching frequency and its side bands did not hit dangerous resonance points at any rotation speed.

MV delivers benefits in multimegawatt wind turbine applications when compared with LV systems. MV systems provide a low-current solution that minimizes cable losses, makes generator design easier and allows the use of a robust MV converter with high availability. The medium-speed concept with PMSG is a compact solution with low weight and the highest efficiency close to the nominal point, compared with all other concepts. Back-to-back tests of the electrical drivetrain demonstrated that the ABB generator and converter meet the requirements of the customer and IEC. Discrepancies between the calculated figures and measurements were within acceptable limits.

This combination of medium speed and medium voltage provides many significant benefits, not only for the customer – the turbine manufacturer – but also for the wind farm operator and end customer.

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Braking news

DC wayside products for energy efficiency in traction

MICHAL LODZINSKI – Although rail and tram are among the most efficient means of transport, they still consume a large amount of energy – especially when acceleration is involved. The amount of energy required to accelerate a vehicle weighing hundreds of tons up to even modest velocities is huge, so any increase in energy efficiency will have significant cost benefits. Regenerative techniques – in which braking energy is reused for acceleration – are well known but still hold much potential. ABB offers a complete suite of energy management solutions that enable braking energies to be better used, resulting in more energy-efficient urban rail transportation systems.

Recycling, or managing, surplus braking energy can reduce overall power consumption by as much as 10 to 30 percent, without the need to invest in new cars or network control systems.

Energy efficiency is a topic important to many industrial sectors and the urban rail-based public transport network is no exception. Even though travel by rail is already much more energy efficient than by most other means, improving energy efficiency even further is important to metro, light-rail and tram operators constantly challenged to reduce operational costs and to provide mass transport in a sustainable manner. ABB offers a complete suite of products to facilitate this – especially products aimed at managing surplus braking energy.

Title picture
Urban rail transport can be made more energy efficient through better use of the kinetic energy usually lost through braking. How does ABB's ENVILINE™ palette of products accomplish this?

Up to 80 percent of the total energy consumption of a rail transportation system is used to actually move the trains and recycling, or managing, surplus braking energy can reduce overall power consumption by as much as 10 to 30 percent, without the need to invest in new railcars or network control systems.

Today, many rail vehicles recycle braking energy. Most of the time, a small portion of this energy can be used to power onboard loads and the remainder can be sent into the electrical power network for reuse by a nearby vehicle. This kind of energy transfer is called natural receptivity. If the energy cannot be recycled in this manner, the network voltage increases and the surplus energy is dissipated in onboard or wayside resistors.

However, recycling or managing the surplus braking energy intelligently can reduce overall power consumption. ABB's ENVILINE™ products offer a way to accomplish this.

The ENVILINE Energy Recuperation System (ERS) reduces energy costs by returning vehicle braking energy to the AC network.

1 The ENVILINE Energy Recuperation System (ERS)

2 ABB's ENVILINE Energy Recuperation System wins prize

ABB received an award at the Railtex 2013 international exhibition for its ENVILINE Energy Recuperation System for DC traction applications that can reduce energy consumption by up to 30 percent as well as help reduce heat generation in underground tunnels and so contribute to efforts to "cool the tube."

New for 2013, the Railtex awards have been introduced to recognize excellence within the railway industry. ABB's award in the electrification category was presented by former England cricketer Phil Tufnell and BBC Radio presenter Garry Richardson at a ceremony held on May 1, 2013 in London.

ENVILINE Energy Recuperation System

The award-winning ENVILINE Energy Recuperation System (ERS) reduces energy costs by returning vehicle braking energy to the AC network ➔ 1 – 2.

As mentioned above, if the energy derived from braking cannot be reused immediately it is often dissipated in onboard braking resistors and wasted. However, the ERS, situated trackside, is able to recuperate this energy by feeding it from the DC traction grid back to the AC grid where it is used to power local auxiliary systems such as air-conditioning, heating, ventilation, lighting, etc. The ERS is an IGBT-based inverter installed at the DC substation and connected in parallel with the existing diode rectifiers ➔ 3-4.

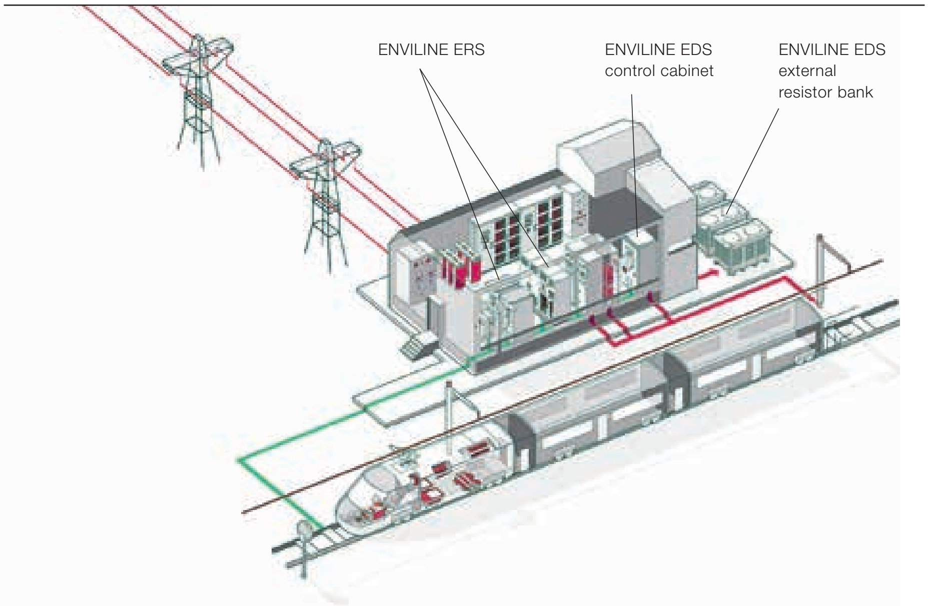
In addition, the ERS can support existing rectifiers, thanks to the active rectification made possible by the bidirectional operation of the system.

When not being used to recover energy from trains, the ERS can be employed to mitigate reactive power in the network. It can also provide active filtering, thus reducing the effect of harmonics. These functions exploit the ability of the IGBT-based inverter to shape the current waveform. This allows independent control of either the active or reactive power. The basic principle is that the DC voltage coming from the traction system is transformed by IGBT inverters to a sinusoidal output waveform. Due to the pulse-width modulation technique used, the output waveform, which is modulated at a frequency of several kHz, does not contain harmonics.

In addition, the ERS can support existing rectifiers, thanks to the active rectification made possible by the bidirectional operation of the system. If there is a need to send extra power to the moving vehicles, the ERS can inject this using the same transformer that is used to send the recuperated energy back to the AC network.

The ERS power range goes from 0.5 to 1 MW, with up to 2 MW units scheduled to be available soon. It can be overloaded

3 The ENVILINE Energy Recuperation System (ERS)



As well as sending energy back into the network with the ERS, it can also be stored by the ENVILINE Energy Storage System.

up to 225 percent for a short period of time and operates with an efficiency of 97.5 percent. Because it has a small footprint and is compatible with new and existing systems, the ERS is easy to install and its modular architecture enables it to be expanded to meet any growth in demand. Low maintenance requirements and a long operating lifetime mean the ERS saves substantial amounts of energy over many years with little intervention. The ERS can reduce the total energy consumption of a rail transportation system by 10 to 30 percent.

ENVILINE Energy Storage System

The recycled braking energy can be sent back into the network with the ERS, but the energy can be stored, too, by using the ENVILINE Energy Storage System (ESS) ➔ 4–6. This is especially useful for those rail transportation authorities who connect their substations directly to the local electric company and who are thus unable to sell surplus energy at attractive rates. The ESS is also of benefit to authorities who may have power supply and quality issues. The ESS is the industry's smallest, yet most modular and flexible, wayside energy storage system. It is equipped with either supercapacitors, for short-term storage and recovery of the surplus braking energy, or batteries, when revenue generation or heavy-duty power provision is of interest. Like the ERS, the ESS can reduce the total energy consumption of a rail transportation system by 10 to 30 percent.

The benefits of the ESS go further: As well as helping to recycle energy, it can also be installed at a specific location to sustain the voltage where large sags occur; it can be used to augment the traction power capacity during acceleration; and the penalties or demand charges associated with high-demand peaks can be reduced by intelligent use of stored ESS power.

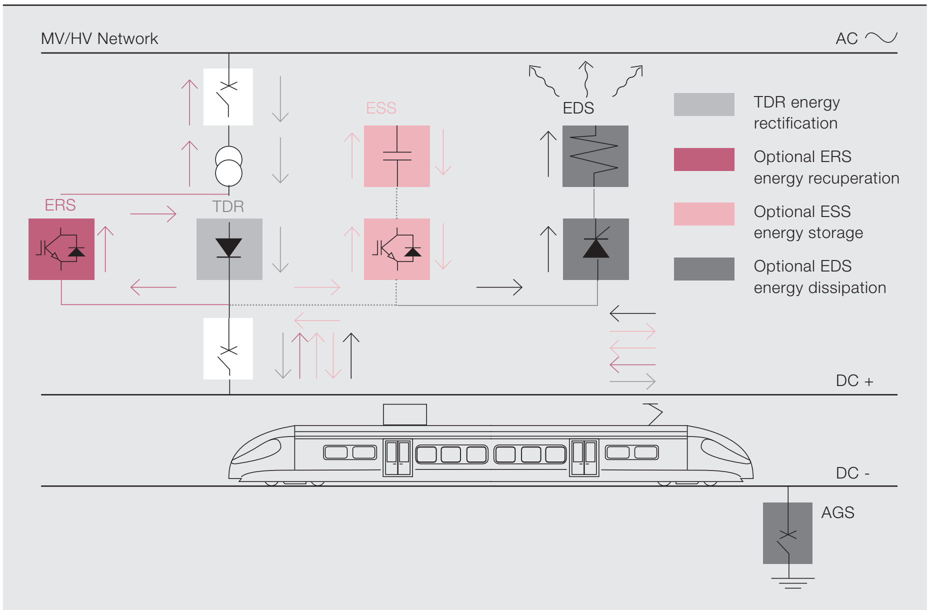
The ESS is compatible with existing train systems and it can be flexibly programmed to ensure optimum operation at each site. Its modular packaging allows independent sizing of power and storage. Operation is further eased by the provision of remote access with multilingual and email notification, energy metering, operational dashboards and downloadable data files. The ESS operates on 600 V and 750 V nominal lines and is expandable to 4.5 MW and 60 MJ per lineup. Parallel configurations are possible for large applications.

Opportunities beyond energy efficiency

On top of being the single best means to improve energy efficiency, the ESS can also become an off-grid traction power supply. In addition to the surplus braking energy, further energy can be added via the traction power line or a small rectifier, usually in between train arrivals. Such off-grid schemes are less expensive and more energy efficient than traditional grid-connected traction power supplies.

The ESS can be installed at a specific location to sustain the voltage should large sags occur.

4 ENVILINE schematic



When coupled with batteries providing larger energy reserves, the ESS can also become a smart grid asset capable of providing emergency power or demand-response services to the local utility.

Retrofit

A very important advantage of both the ERS and the ESS is that they are designed for retrofit. In refurbishment projects, all fixings and connections are predefined. This presents a tougher challenge than fitting new equipment in a new installation.

On top of being the single largest means to improve energy efficiency, the ESS can also become an off-grid traction power supply.

Both systems are based on a modular architecture, which allows independent scaling of power per single system. In order to achieve the best return on investment, it is necessary to evaluate the available surplus energy, estimate the power of the system to be used and choose the optimal connection points. Both products are transparent to the existing system, which means they can be isolated without interrupting normal operation.

ENVILINE Energy Dissipation System

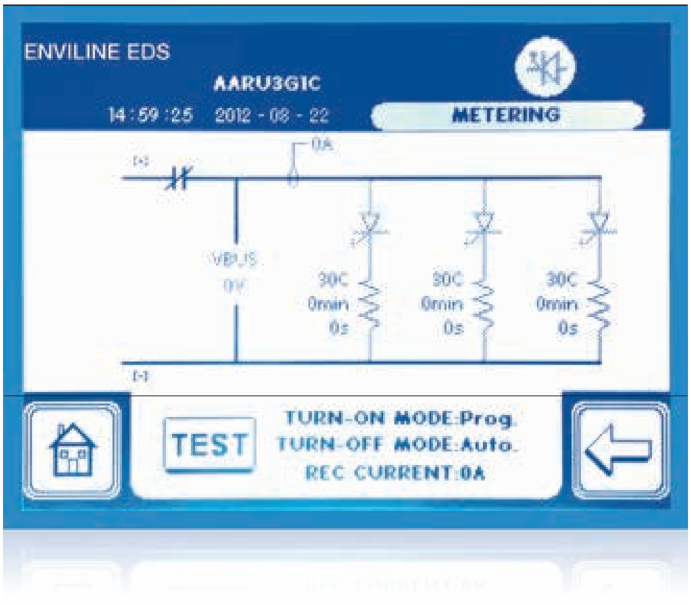
In certain cases, some of the regenerated energy cannot be used and must be dissipated. However, installing braking resistors on the vehicle to do this adds weight and increases maintenance effort. The ENVILINE Energy Dissipation System (EDS) provides a low-cost solution to this problem in DC rail systems. By deploying the wayside EDS instead of onboard resistors, the rail operator can reduce vehicle weight and energy consumption, eliminate heat generation in tunnels or enclosed stations and deploy a solution that is easy to access and maintain.

The EDS senses the rising line voltage caused by regenerated or surplus energy and connects an appropriate resistive load to maintain the voltage within safe operating limits, avoiding the need to use (and wear out) the mechanical brakes. The EDS consists of an indoor power control cabinet and an outdoor resistor bank. The system ensures track receptivity during regenerative braking by dissipating the surplus energy that cannot be absorbed by other onboard loads or nearby trains. The EDS is compatible with any new, or already installed, DC traction power substation. It can also operate in coordination with wayside energy storage

5 The ENVILINE Energy Storage System (ESS)

6 ESS batteries and converter cabinets in an installation in Philadelphia, PA, United States

7 User-friendly EDS touch screen



and energy recuperation systems to ensure that the braking energy is recycled effectively and that any dissipation into resistors occurs only as a last resort. The controller cabinet can be mounted directly in the DC switchgear lineup or separately with other equipment such as negative disconnects and automatic grounding switches.

The resistor bank is placed outside the substation, where the heat can be dissipated passively ➔ 3. This fan-free solution is not only economical but is also noise-free, both from the acoustic and EMC standpoint.

The EDS not only protects against overvoltage, but it also improves the power quality and operational reliability. It has other advantages too:

– Lower cost than chopper-based designs
– Lower operational and maintenance costs than onboard units
– Easy maintenance with remote monitoring and access
– Advanced controls with remote testing capability and programmable firing to ensure optimum performance and to avoid false triggering ➔ 7
– Time balancing of the GTO and resistor operation to share operational wear and maximize life expectancy

The ENVILINE series includes other products, such as the traction diode rectifier (TDR) used to convert AC to the DC commonly used in urban public transport infrastructures ➔ 4.

ABB's long experience in traction means customers will receive expert advice in choosing the ENVILINE solution that precisely meets their requirements – allowing them to benefit from a comprehensive, flexible and high-performance solution that will deliver cost and energy savings for many years.

For more information on ENVILINE, see www.abb.com/enviline or write to enviline@pl.abb.com.

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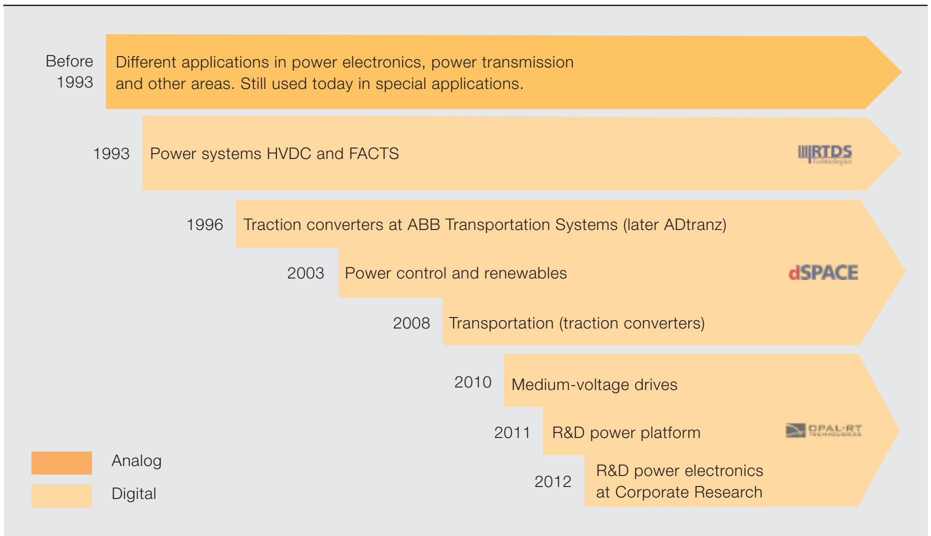
Need for speed

Real-time simulation for power electronics in railway applications and beyond

ROXANA IONUTIU, SILVIA MASTELLONE, XINHUA KE, ERICH SCHEIBEN, NIKOLAOS OIKONOMOU, DIDIER COTTET, DANIEL STUMP – Digital real-time simulation (RTS) has revolutionized the power electronics control system technology chain by bridging the gap between development of advanced control technology concepts and deployment of successful products. RTS meets possibly its most challenging application in power electronics, where the requirement for simulation performance of complex switched systems pushes the boundaries of the present technology. For many years, ABB has pioneered ever more sophisticated RTS tools to guarantee product reliability and low-cost, efficient testing for the next generation of high-performance power electronics systems.

1 History of RTS at ABB



Simulation tools have supported the development of engineering systems since the early 1950s, when analog and digital computers started to appear. The powerful computing power available today now allows fast simulation of complex systems. This is especially valuable in control systems simulation where, in order to test the controller running at its nominal operation speed, the computer model must run at the same rate as the actual physical system, ie, in real time.

In today's power electronics industry, RTS is a critical player across several stages of the technology chain that enables the transfer of new control concepts into successful power electronics products.

From the first custom analog versions to today's high-end, commercially available digital platforms, ABB has long relied on RTS to support the advancement of its power electronics control technologies ➔ 1. RTS is essential not only for developing better control concepts, but also for improving software and product quality through early-stage, time-efficient testing. The key feature of real-time simulators is the hardware-in-the-loop (HIL) technology that allows the control software, running on the actual control hardware platform (ie, DSPs, FPGAs) to be connected to software models that emulate the power electronic converters and their environment. The HIL enables the controller to operate as if it were controlling the real system with its full features.

Modern power electronics systems, with their exceptionally fast dynamics, are a nontrivial challenge for simulation in real time. New ways to handle the design of models with variable structure, using constrained simulation time steps and ensuring minimal computational effort, are required.

Today, ABB uses RTS widely and is committed to advancing RTS technology to meet growing computational demands, cope with increasing system complexity and support the advancement of control algorithms.

Two highly interdependent criteria – satisfying critical timing constraints and ensuring fast and accurate physical models – lie at the heart of real-time simulation.

The technology chain

The technology chain is the process that regulates how technology concepts are improved from one generation to the next. RTS plays a critical role in the technology chain for ABB converter systems.

This process begins with the knowledge of the existing technology (generation k-1) and guides the formation of new ideas, leading to an improved product. These have to be implemented, tested and verified before the control concept can become part of a product as generation k ➔ 2.

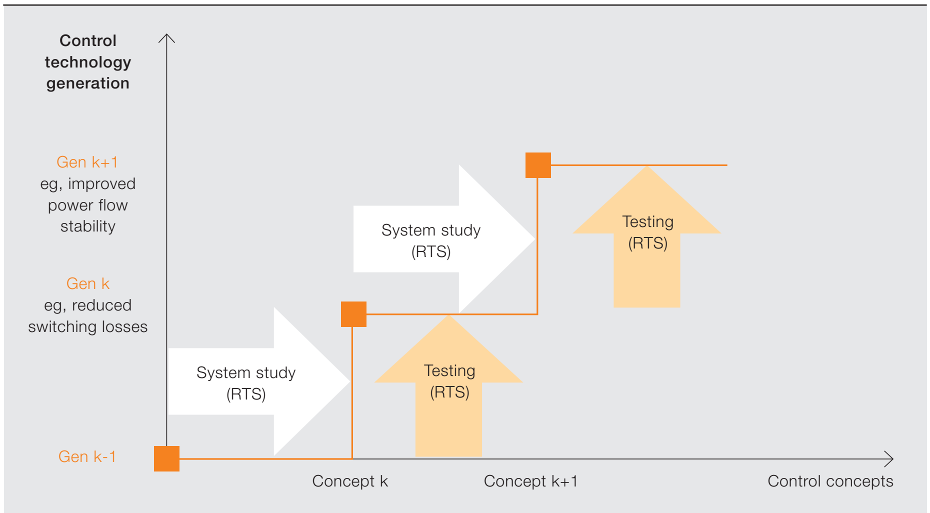
RTS supports the concept formulation phase by providing an environment in which to investigate and gain a fundamental understanding of system behavior before defining a control concept.

Once a control concept is developed and implemented in the converter, it has to be rigorously tested according to defined standards before the product can actually be deployed. This phase encompasses several testing steps in different environments, from offline simulation to real-time simulation and finally on the real system itself. Typically, offline simulations are insufficient to reproduce the closed-loop system behavior with the actual integrated control software and hardware, and are computationally too expensive for the

Title picture
Real-time simulation is an essential tool for developing the very sophisticated power electronics systems used in so many common applications, like railway vehicles.

In today's power electronics industry, RTS is critical to several stages of the technology chain that enables the transfer of new control concepts into successful power electronics products.

2 The technology chain



required accuracy. Furthermore, testing converter software on the real system can be expensive (daily testing can cost up to $60,000), time-demanding and even prohibitive for extreme parameters such as short circuits, excessive voltages or currents, large loads, high speeds, etc.

Real-time simulation is the key for handling the complexity of todays' systems. It compensates for the shortcomings of offline and onsite testing by adopting the powerful concept of online emulation. RTS reproduces the complexity of the real system in real time while preserving the benefits of a simulation: flexibility, fast implementation, easy debugging and wide test coverage. This enables control software to be thoroughly tested and improved during the early development stages, thereby guaranteeing software and product quality and shortening the final commissioning process on the real system.

Specialized teams of engineers are constantly working to meet the technological challenges posed by the high requirements on the RTS systems.

Challenges in real-time simulation

In order to guarantee reliable control system development and testing, the RTS must represent, with a high degree of accuracy, the real environment in which the controller operates. In the case of traction applications, for instance, the controller operates on the power electronics of the traction converter inside the train. The RTS emulates this environment using special hardware and software configurations, where complex mathematical models, collectively called the "physical model," replace the converter and the train, while the controller remains connected in a closed-loop fashion with this physical model ➔ 3. Based on the inputs received from the controller (eg, switching pulses for operating the semiconductor devices inside of the converter), the physical model computes the necessary outputs (such as voltages, currents and speed) and sends them back to the controller for the next simulation cycle. Relevant states of the physical model can be visualized, monitored and manipulated through a user interface ➔ 4.The traction RTS has, in addition, a virtual vehicle control unit on which the desired tractive effort or speed reference are set in the same way as on the real vehicle by the driver ➔ 3.

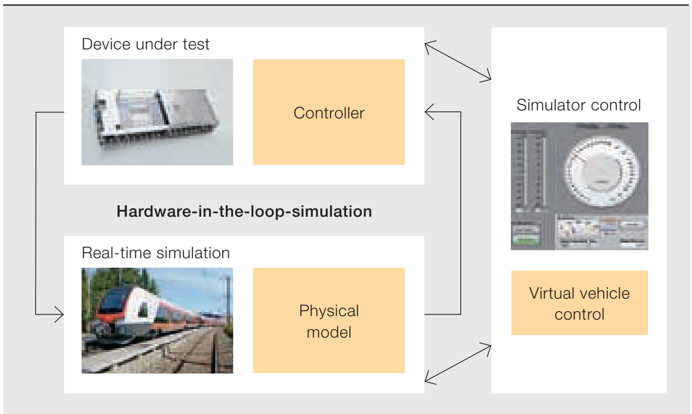
Within the ABB group, several real-time simulators have been developed in cooperation with various RTS system vendors, each one specific to a particular business sector ➔ 1.

The simulators can differ in scale, in the hardware used or in the specifics of plant modeling, but they are all, nevertheless, challenged by the same fundamental issues. In particular, two highly interdependent criteria – satisfying critical timing constraints and ensuring fast and accurate physical models – lie at the heart of real-time simulation.

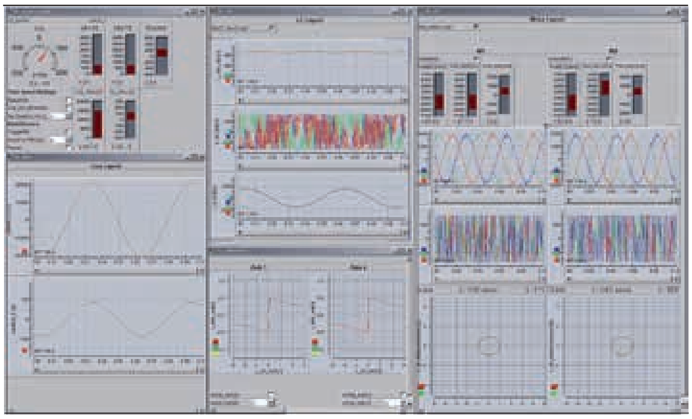
Critical timing constraints

A critical requirement for an RTS system is to achieve synchronization between

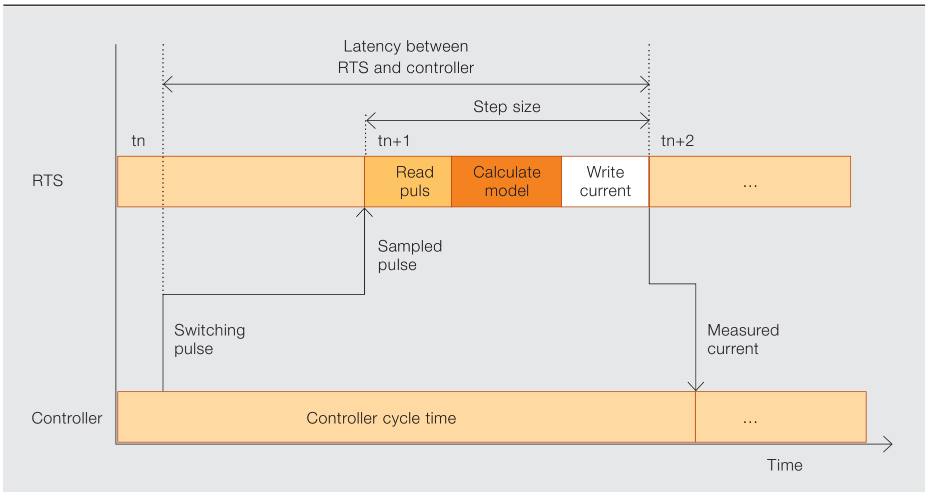
3 RTS setup for HIL simulation, with virtual vehicle control unit



4 RTS user interface for visualizing the state of the plant in real time and for directly interacting with the physical model



5 A maximum delay of twice the RTS step size occurs between the controller sending switching pulses to the RTS and the corresponding response.



real time and simulated time. In other words, the simulated inputs, outputs and states reached on the RTS after a certain simulation time should be the same as those on the real system when the same amount of time has passed. The rate at which the real-time clock achieves this synchronization is determined by the step size of the RTS, the length of which must be carefully chosen. On the one hand, the RTS step size must be as small as possible in order to minimize the latency of the simulated system, but, on the other hand, be long enough to allow the RTS to complete the operations required in one simulation step without causing overruns ➔ 5.

Fast and accurate physical models

Power electronics' high-frequency switching (kHz) imposes controller cycle times in the order of 100 to 300 µs. These, in turn, impose yet shorter cycle times on the RTS (less than 60 µs). Ensuring fast and accurate simulations with step sizes in the microseconds range is especially challenging for power electronics systems compared with applications with slower dynamics – for instance automotive or robotics, where RTS step sizes can reach milliseconds.

ABB's RTS systems win this challenging race against time thanks to the dedicated hardware and software solutions offered by vendors, coupled with ABB expertise in power electronic circuit modeling and simulation. As fast hardware alone is insufficient, the physical models and the numerical routines to solve them must also be optimized for maximum efficiency, an effort into which ABB invests significant know-how.

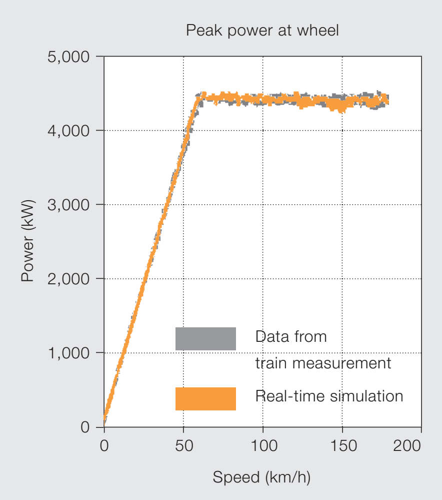
One of the most difficult challenges is the processing of the switching pulses received from the controller and sent to the converter switching devices – eg, IGBTs. To accurately simulate these, a granularity even finer than the RTS cycle time is required and this is achieved using FPGA technology [1]. To simulate the converter in rectifier mode, internal switching events caused by self-commutating diodes are also modeled. The frequent changes in switch positions and the nonlinear nature of some of the model components add complexity to the modeling and simulation task, as different switch configurations must be recognized and solved immediately during runtime. While such problems can be solved in offline simulations using sophisticated numerical time integration algorithms, these methods are computationally too expensive for real-time use, hence the need for special modeling and simulation solutions. Within ABB today, highly complex systems from different power electronics domains can be simulated on appropriate real-time platforms ➔ 1. An ABB dSPACE-based simulation platform has, for example, been used for traction RTS.

Vehicle in the lab

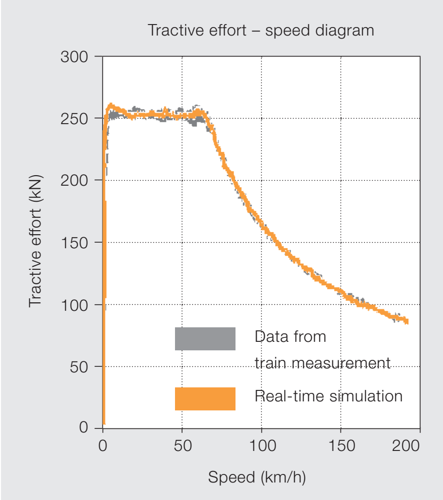
The RTS in the transportation product group provides flexible hardware and software setups for railway applications

6 ABB traction converter with PEC 800 controller

7 Acceleration test for NSB FLIRT



7a Real-time simulation



7b Results from measurements on the train match the simulations closely.

The future calls for smart simulation solutions that reduce the modeling effort for switched systems of increasing complexity, while satisfying the required speed and accuracy.

spanning power ranges from 100 kW to over 6 MW, for single- or three-phase AC, for DC and for multisystem or diesel electric systems.

The RTS modeling domains cover the locomotive power supply (overhead line, pantograph and main circuit breaker), transformer, traction converter (line converter, DC link with tuned filter, motor converter), motor, gear and axle, auxiliary converter, diesel engine generator, energy storage and wheel-rail contact. The RTS physical models are easily configurable and can meet diverse customer requirements by supporting various types of transformer setups, converter topologies (two- or three-level) or driven axle arrangements (single-axle or bogie-control), etc.

One of the projects running on the RTS involves the FLIRT electric low-floor multiple unit made by the Stadler Rail AG company. ABB supplies the traction converters, traction transformers and low-voltage components for this product → 6. The transformer and the converter are responsible for transforming the single-phase static frequency AC power from the supply line into the three-phase variable-frequency power needed to drive the motors and turn the wheels. For this, the complete conversion chain, from power supply down to the wheel-to-rail contact, is modeled on the RTS, so that the control software and hardware can be tested in a closed loop and as if it were in the actual train.

An important train performance parameter is the evolution of tractive effort as a function of speed. This characterizes the power of the train. For the FLIRT, a 4,500 kW peak power at wheel is attained with a maximum tractive effort of 250 kN and maximum speed of 200 km/h. The tractive effort versus speed characteristic can be simulated on the RTS → 7. Until the 4,500 kW peak power at the wheel is reached, a 250 kN maximum (constant) tractive effort is applied, after which the tractive effort decreases while the train accelerates to its maximum speed of 200 km/h, maintaining constant power. The curves obtained on the RTS closely match those obtained from measurements performed on the train itself, demonstrating the reliability of the RTS simulation.

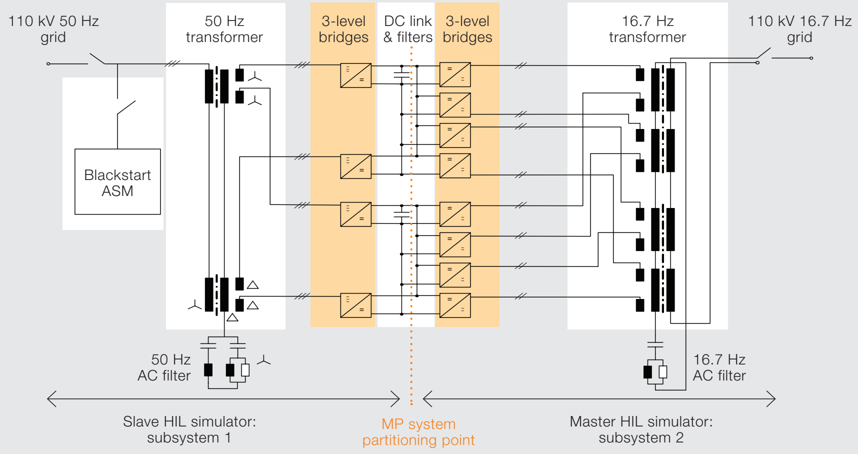
80 MW in the lab

Another challenging project involved the simulation of a static frequency converter responsible for the energy exchange between the three-phase 50 Hz national grid and the single-phase 16.7 Hz railway grid. A parallel processor implementation for the RTS was the solution for a problem of such large scale → 8.

RTS in the future

Today, the impact of RTS on control innovation in the power electronics industry is unquestionable. Unsurprisingly, there is a demand for even more efficient testing and for even more complex test scenarios – and it is here that automated software testing (AST) will play a major role. AST provides an environment for running and

8 Multiprocessor RTS configuration for a railway frequency converter: 3-phase 110 kV / 50 Hz to single phase 110 kV / 16.7 Hz.



- Components to be simulated:
  50 Hz grid with various fault situations
  50 Hz grid blackstart asynchronous machine (ASM)
  50 Hz transformer (linear)
  50 Hz AC filter (in Y)
  50 Hz AC/DC converters with 12 phases
  (each phase can be on or off)
  DC link with voltage limiting unit and various filters
  16.7 Hz DC/AC inverters with 16 phases
  (each phase can be on or off)
  16.7 Hz transformer with saturation
  16.7 Hz grid with load and various fault situations
- Number of I/Os to be handled:
  200 fast I/Os and around 750 slow I/Os
- Maximum step size: 60 µs

Problem: It is impossible to adequately simulate such a system with a single simulator due to the system's large size and complexity.

Solution: a multiprocessor system setup with two complete HIL simulators
In a multiprocessor system setup, two or more simulators must exchange measured/calculated quantities before and after their calculation since one subsystem requires the output of the other.

This arrangement can produce signal inconsistency, which leads to incorrect simulation results or even instability, if system partitioning is not properly done. Thus, the system partitioning becomes the key factor for the desired performance. In this application the system is partitioned into two subsystems from the DC link, where the system quantities are "relatively static."

All the 50 Hz-side components together with the DC link and its various filters are simulated on one simulator (slave) and the rest on the other (master) in parallel.

recording operator-free routine control tests automatically, thereby significantly shortening the control testing and commissioning phase.

Regarding RTS modeling, the future calls for smart solutions that reduce the modeling effort for switched systems of increasing complexity. Current techniques demand significant understanding of the entire system behavior and deep mathematical insight to obtain models and simulations that meet the required speed and accuracy demands. As power electronics systems become increasingly complex, highly optimized simulation solutions that exploit model hierarchy and parallelism gain importance. Looking in this direction, the novel quantized state system (QSS) approach [2] could revolutionize the nature of discrete simulation. In QSS methods, time is no longer discretized, rather, the state variables are quantized, allowing systems with frequent topology changes, such as power electronics systems, to be simulated more efficiently using a discrete event formalism.

Whether involved in power generation or transmission, renewables, industrial drives or electric trains, RTS for power electronics systems within ABB, in close collaboration with simulation platform vendors, will continue to push its boundaries. RTS will exploit improving computer performance, smarter models and faster solver algorithms to enable control technology to quickly innovate from one generation to the next across the technology chain.

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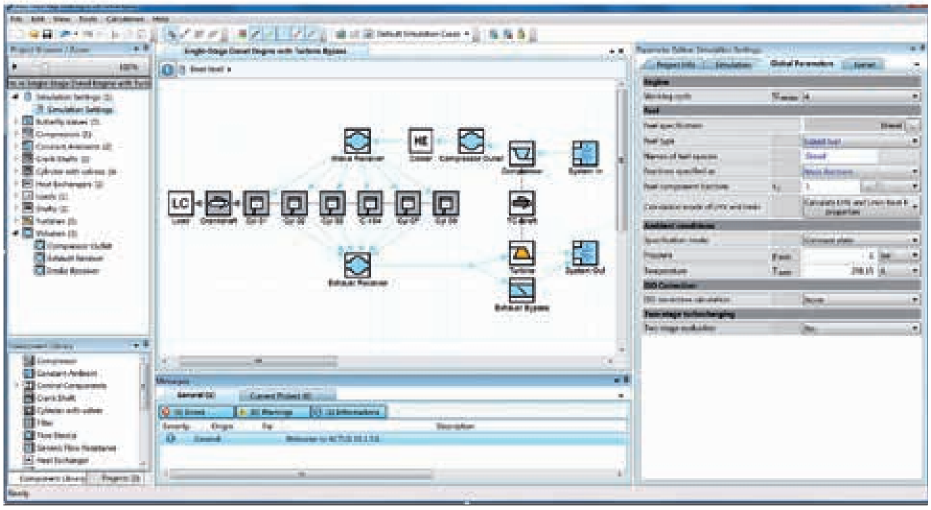
[1] P. Terwiesch *et al.*, *"Rail vehicle control system integration testing using digital hardware-in-the-loop simulation,"* IEEE Transactions on Control Systems Technology, vol. 7, no. 3, pp. 352, 362, May, 1999.
[2] F. Bergero *et al.*, *"A Novel Parallelization Technique for DEVS Simulation of Continuous and Hybrid Systems,"* Simulation, in press, 2013.

Turbo boost

ACTUS is ABB's new simulation software for large turbocharged combustion engines

THOMAS BÖHME, ROMAN MÖLLER, HERVÉ MARTIN – The performance of turbocharged combustion engines depends heavily on the performance of the turbocharging system itself. The interplay between the engine and the turbocharging system is complex and simulation is an essential tool for understanding this interaction and how best to match the engine components. Today, most engine manufacturers perform simulations to optimize their engine systems' designs. The vast majority of manufacturers rely on commercial simulation tools, which are sometimes supplemented by in-house developments for specific tasks. While today's commercially available tools are usually of very high quality and offer an extremely wide range of functionality, ABB continues to rely on in-house simulation software for its engine simulation needs. The use of in-house software allows ABB to fully customize the simulation to suit the specific needs the company has as a manufacturer of turbochargers for large-bore combustion engines. These needs range from selection of optimal turbocharger specifications in sales to research applications for test benches, turbocharger product development and the development of turbocharging concepts.



1 ACTUS user interface graphical editor showing a model of a simple six-cylinder, single-stage turbocharged engine with a turbine bypass valve.

ACTUS consists of two parts: A modern user interface with a graphical topology editor for setting up the simulations and a simulation kernel for performing the calculations.

The simulation of turbocharged engine systems has a long tradition in ABB. The first digital computations were performed in the 1960s with the introduction of the first digital computers [1,2]. These computational tools were continuously improved and extended. In the early 1980s, the existing calculation methods were combined into a single simulation platform called SiSy (Simulation System) that has been continuously extended since then [3].

After more than 20 years of development of SiSy, it became increasingly difficult to further extend the software due to its monolithic software design, so the decision was made to replace the software with a new simulation tool based on a modern, modular software design. The new simulation tool was named ACTUS (advanced computation of turbocharging systems). The software consists of two parts: a modern user interface with a graphical topology editor for setting up the simulations and a simulation kernel for performing the calculations.

Graphical user interface

In the graphical user interface, the engine is built by combining components from a library of distinct elements such as pipes, valves, compressors, cylinders, shafts, etc. and defining their possible interaction through fluid, mechanical, heat, or signal connections ➔ 1. Once the topology is defined, the parameters of each component are specified in the parameter editor (on the right of the figure). A special simulation case editor allows multiple consecutive simulations to be set up – to simulate multiple engine load points in one simulation run, for example. The user interface also gives convenient access to a broad database of detailed performance data for all ABB turbochargers available since the 1970s.

Simulation kernel

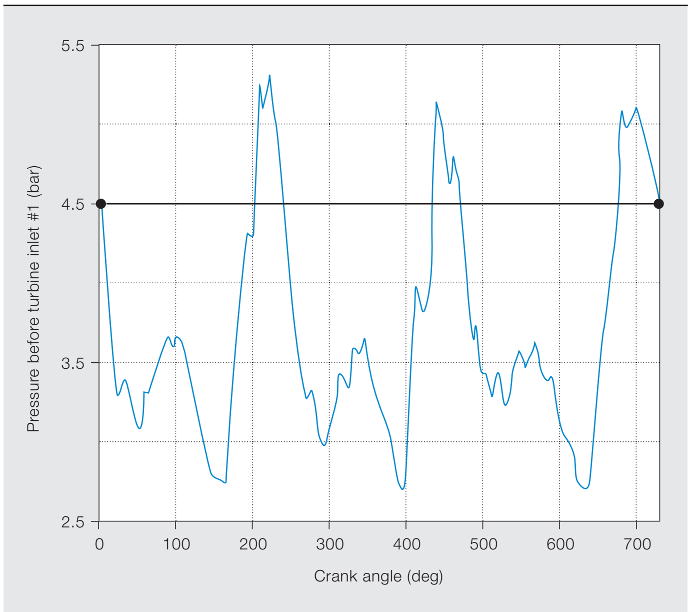
The second part of ACTUS, the simulation kernel, solves the model equations for the system and computes the results. The primary focus of the simulation is to predict the most relevant aspects of the whole engine system rather than focusing on specific, detailed aspects. While nowadays it would be possible to simulate the gas exchange of an engine cylinder with three-dimensional computational fluid dynamics, such a level of detail would not be suitable for a system level computation: The resulting computational time would be prohibitive for use in optimization and, even more importantly, such a calculation would require detailed knowledge of all geometries of the engine, which is typically not available to ABB.

Therefore, the models used in ACTUS are simplified models derived from physical first principles. The system simulation of a turbocharged engine system requires a large number of such simplified models from a range of different disciplines. This includes mechanical models for the crankshaft, and turbocharger shafts and bearings; thermal models for heat transfer; chemical models for emissions; and thermodynamic models for gas properties as well as for compression, expansion, fluid flow and storage.

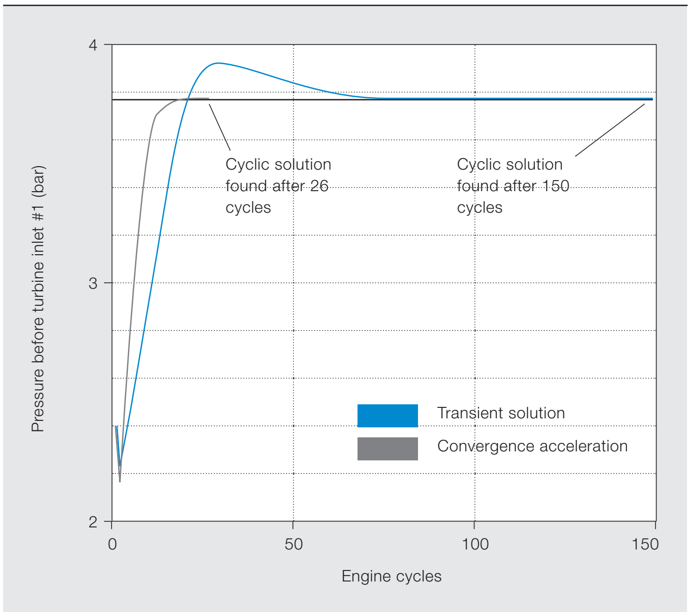
For complex processes, such as the cylinder combustion, the physical first-principle models are commonly complemented by empirical model extensions. These have been derived from the literature or from research collaborations, or have been developed internally within ABB.

Title picture
Only simulation software that has been developed in-house can hope to tackle the immense complexities of engine turbochargers.

2 Pressure before turbine inlet #1 over one engine cycle for a steady engine operation point (at full load)



3 Benefit of convergence acceleration: Instead of requiring 150 calculation cycles in transient mode, the solution is found after 26.



The sales department use ACTUS to select optimal turbocharger specifications for a particular engine – a task most customers rely on ABB to do.

ACTUS convergence acceleration

As most large-bore engine systems run under a constant load for long periods, the constant-load operating points are those of greatest interest for design optimization. Due to the inherently unsteady nature of the combustion engine process, a constant engine load point is not a steady state but rather a situation that exhibits periodicity, as can be seen, for example, from the pressure trajectory near a turbine inlet over one engine cycle → 2.

The solution is periodic when all dynamic states within the system match the initial state after the cycle completion. The most common approach used to determine such a periodic solution is to run a transient simulation long enough for all initial disturbances to decay. Due to the high rotational inertias of the turbocharger and crankshafts, typically more than 100 engine cycles are needed to obtain the cyclic solution → 3. In order to speed up such simulations, ACTUS employs an optimization method, called convergence acceleration, that significantly reduces the number of cycles needed to obtain the cyclic solution. This allows steady-state operating conditions for typical engines to be calculated on a standard PC in a matter of seconds.

ACTUS Match

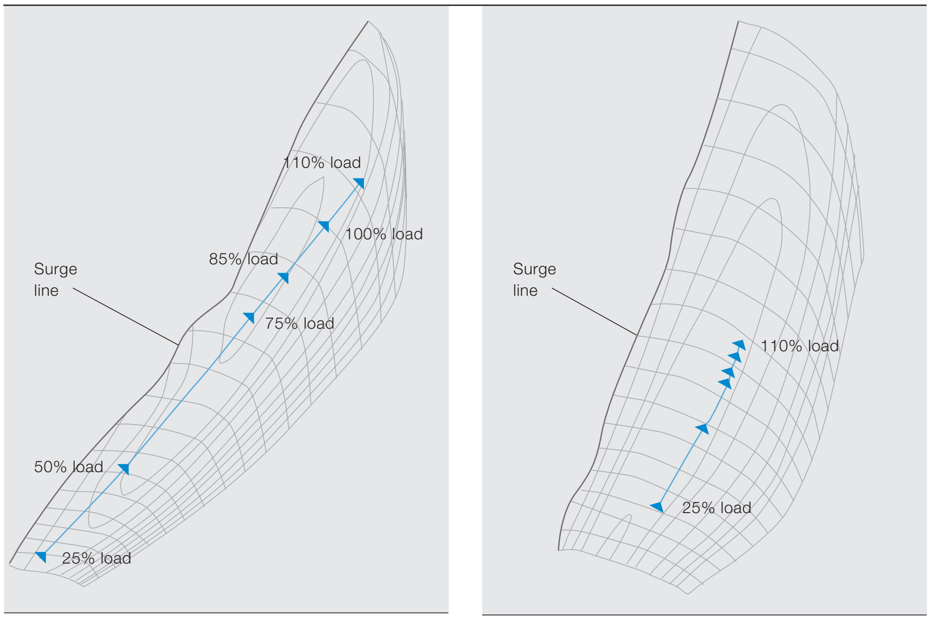
This convergence acceleration is coupled with a unique feature called ACTUS Match. ACTUS Match allows the calculation of the set of simulation input values that will result in a certain desired set of simulation output values. This is useful as system design applications often need to determine a system configuration that yields a desired result. For example, a common task in turbocharger matching is to determine the turbine size such that the engine will operate with an air-to-fuel ratio defined by the engine manufacturer and a given load. From a simulation standpoint, this is a nontrivial task as the resulting air-to-fuel ratio is typically not an input to the simulation, but rather a result depending on the charge air pressure, which in turn depends on the effective turbine area (size).

Here, ACTUS Match allows the required turbine to be determined while, at the same time, taking into account the amount of fuel required to accommodate the desired engine load. ACTUS Match performs this task directly and with only slightly more overhead than a single standard simulation. Most simulation tools require the use of an external optimization process for such applications, which results in significantly increased run times and complexity for the user. This high computational performance allows ACTUS to be used in a very efficient manner for design studies and optimizations.

Sales application

ACTUS was introduced in 2012 and is now widely used within ABB. The soft-

4 Typical operating lines for a two-stage turbocharged engine compressor for a power plant application



4a Low-pressure compressor

4b High-pressure compressor

ware has more than 30 users in sales and research departments and at ABB locations worldwide.

A typical use within the sales department is for the selection of an optimal turbocharger specification for a particular engine (in fact, most customers rely upon ABB for this). Starting with key engine data and, if available, measurements from previous similar engines, a simulation model of the engine is constructed. The model is then used to determine the most suitable turbocharger.

For complex engine systems, such as a two-stage turbocharged engine with a turbocharger bypass as a control element, this becomes a complex task. Typically, the engine manufacturer will first define the desired operating conditions for the engine. ABB's task is then to select a compressor and turbine configuration such that the turbocharging efficiency and, thus, the engine efficiency, is maximized. At the same time, the design has to satisfy a series of other constraints such as a given control reserve for the bypass, a minimal distance from the compressor surge line, maximum admissible rotational speeds of the turbocharger and maximum allowable turbine inlet temperatures.

Here, the ACTUS Match feature significantly reduces the throughput time required for the specifications from hours to minutes ➔ 4.

Research applications

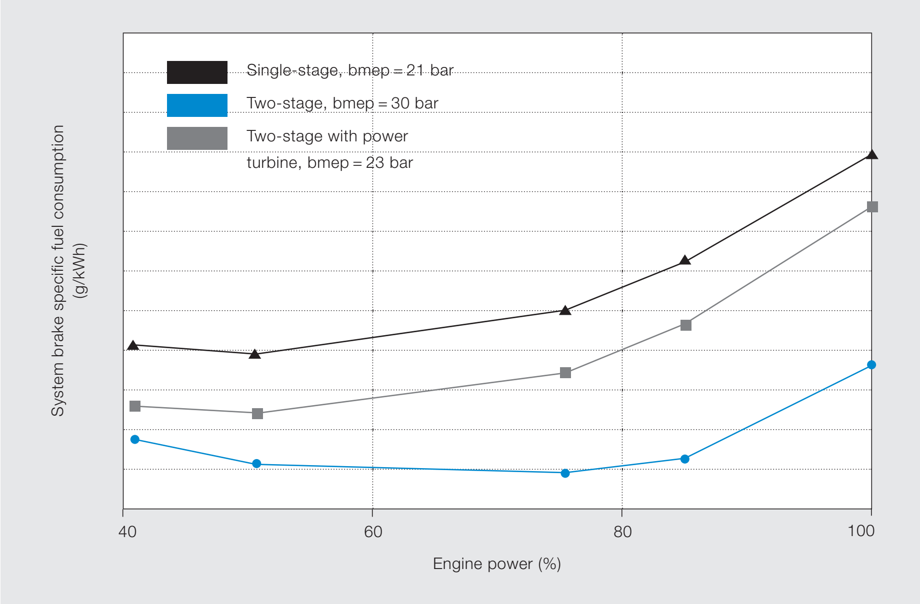
In the turbocharging engineering division, ACTUS is used to investigate new turbocharging concepts and their impact on the combustion engine. A number of these studies were presented at the 27th CIMAC World Congress in 2013 [4,5,6].

One current trend in turbocharging is toward two-stage turbocharging. This allows significantly higher pressure ratios to be used. While the benefits of two-stage turbocharging are well understood for four-stroke combustion engines and several engine manufacturers already offer engines with two-stage turbocharging, the potential for large two-stroke engines is currently not fully understood. In order to gain such understanding, simulation studies were performed showing the potential for total fuel savings at different load conditions [4] ➔ 5.

In the reference case (top curve), the engine is turbocharged by a single-stage turbocharger and a brake mean effective pressure of 21 bar, as is common today. The study shows that by using two-stage turbocharging and either increasing the brake mean effective pressure or employing a power turbine or waste heat recovery system, the overall fuel consumption of the system can be reduced significantly. It should be noted that these results are a prediction based purely on simulation models that have been utilized for the purpose of exploring the potential of future turbocharging

ACTUS is also used within product development to predict design parameters for the next generation of turbochargers.

5 System fuel consumption comparison for different two-stroke engine turbocharging topologies



In the turbocharging engineering division, ACTUS is used to investigate new turbocharging concepts and their impact on the combustion engine.

options, well before any experimental results would be available.

In addition to the applications described above, ACTUS is also used within product development to predict design parameters for the next generation of turbochargers. ACTUS also features a mode in which turbocharger performance can be evaluated based on measurement data and compared with expected values. Recently, ACTUS was extended so that it can be used to determine the specifications for new two-stage turbocharger test benches at ABB sites. Due to the complexity of two-stage operations, the specification methods previously used were no longer suitable.

Turbocharging the future

The detailed understanding of the turbocharging process and its continuous improvement have always been strengths of ABB. Part of that understanding has been derived from the long-standing tradition of system level simulations of large-bore combustion engines. ABB's new ACTUS simulation tool builds upon that tradition and provides a modern and sound basis for future simulation needs.

As an in-house simulation tool, ACTUS allows very efficient system-level simulations and is highly customized to ABB's specific needs as a turbocharger developer and manufacturer. This allows ABB to continue to support customers in determining the optimal turbocharging solution for their engines and to shape new turbocharging concepts and solutions that enable ABB's customers to further improve engine performance and to comply with future emission legislation.

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Model train

Combining electromagnetic and mechanical simulations for better drivetrain designs

TIMO P. HOLOPAINEN, TOMMI RYYPPÖ, GUNNAR PORSBY –
The power flowing to a typical rotating machine, such as a pump or compressor, passes through a complex mechanical and electrical transmission chain on its journey from the grid to the target device. This power must flow through all the components in the chain and each of these has to withstand the loading involved. This loading, including extreme forces brought on by resonance or failure modes, appear as torsion in the mechanical components.

Mechanical modeling is able to simulate this behavior. However, electromagnetic effects, in the form of electromagnetic stiffness and damping, may also affect vibration behavior, but these effects have been difficult to incorporate into a holistic analysis of the drivetrain. Simulating the electromagnetic fields of an electrical machine is an activity in which ABB has long experience, and this experience is now being combined with mechanical simulation techniques to enhance drivetrain torsional analysis.

1 A typical drivetrain, consisting of a blower (left), a blower shaft (through the yellow cover), a gearbox (under the front yellow acoustic enclosure) and a motor with a cooler above (right).

A typical power transmission chain consists of a driven machine – such as compressor or pump – an optional gearbox, a motor, an optional frequency converter and the power grid. These individual components are mechanically and electrically coupled and the power needed to perform the final useful work, such as accelerating fluid in a pump, flows through each of them. All the components must endure this power flow, which appears in mechanical components as torque.

Nominal, or rated, torque is the basis of component dimensioning, but extreme loads can present themselves in resonance or failure conditions. Resonance vibrations occur when there is an excitation at one of the natural frequencies of the system – the lowest natural frequency of a large drivetrain is around 20 Hz, for example. Contributing harmonic excitations originate from all the main components: the driven machine, gearbox, motor, etc. [1] ➔ 1.

Title picture

Complementing mechanical models with electromagnetic simulation knowledge can improve the quality of rotating machinery design. How can these two disparate model worlds be combined?

Torsional analysis of drivetrains

The aim of a torsional analysis is to predict the vibration behavior of a drivetrain. This information is needed so that harmful vibrations do not appear under any operational conditions. At worst, shortcomings in this analysis may lead to an unpredicted interruption of operation or catastrophic failure.

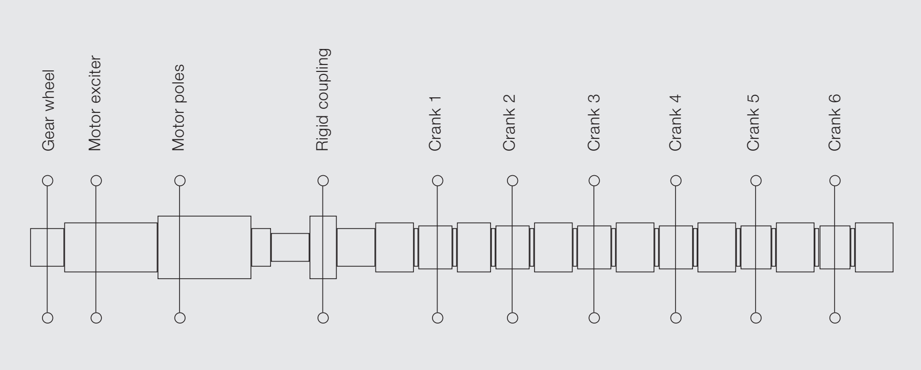
In most industrial cases, each drivetrain element is designed and produced by a different manufacturer, and often without due consideration of the other elements. This poses a challenge to the system integrator as a characteristic feature of drivetrain vibration is the interaction of these elements, which requires the system torsional vibrations to be analyzed as a whole. It is common practice for the system integrator to prepare a torsional model based on the data provided by the individual component manufacturers. Using this model, the system integrator, together with the manufacturers, tunes the drivetrain design to fulfill the torsional vibration requirements.

ABB has responded to drivetrain simulation challenges by developing simple, portable models that accurately describe electromagnetic interaction.

The torsional model applied is usually one-dimensional. This is practical because the full numerical model of each component would include information that is superfluous to the torsional analysis. In addition, the full model could unveil confidential product information. Therefore, the component models of torsional drivetrains are intended to be simple, portable and accurate enough for the job at hand but not overwrought ➔ 2.

Traditionally, an electrical machine in a drivetrain is modeled based on the stiffness and inertia characteristics of the rotor. This kind of rotor model is easily incorporated into the system model. The electromagnetic effects are usually neglected, even though they may affect the vibration behavior by introducing electromagnetic stiffness and damping. One of the reasons for neglecting these effects is the difficulty of incorporating the electromagnetic part of the motor model into the drivetrain model [2].

2 Schematic drawing of a torsional model for a motor-driven piston-compressor



The key is the calculation of electromagnetic spring (torsional stiffness) and damper coefficients.

Simulation of electromagnetic fields

To accommodate the typical behavior of rotor and stator electromagnetic fields, two-dimensional numerical models are often used to describe an electrical machine's electromagnetic behavior ➔ 3. The figure shows a snapshot of typical magnetic fields and currents in an electric motor during operation. Magnetic flux density and flux lines are shown in the upper left part of the figure. The magnetic field lines flow in the plane of the figure; the electric currents in the rotor and stator windings flow in the perpendicular direction. The electromagnetic field rotates around the shaft center. The rotor accompanies the rotating field either synchronously or slightly lagging. Typically, electromagnetic fields, even in steady-state operation, must be simulated in the time domain. The maximum length of the simulation time step is determined by the accuracy required but is usually some tens or hundreds of microseconds.

Simulation is made difficult by the variation in the rotor/stator air gap geometry caused by the machine rotation (the nonlinearities introduced by the magnetic saturation of the constituent steel also complicate matters). The main task of electrical machines – converting electrical energy to mechanical power – is carried out in the air gap, so a diligent mathematical analysis of electromagnetic field behavior in the gap is essential for accurate calculation of the mechanical torque.

Coupled analysis of electromagnetics and drivetrain mechanics

One way to simulate a torsional system is to make the mechanical drivetrain model part of the electrical motor model. In this case, the electrical motor model will use a varying rotor rotational speed – one that is determined by the motor torque, load torque and the equations of motion. Such a simulation is relatively straightforward as long as the mechanical rotor model of the drivetrain is simple and uses well-known elements. This kind of model enables simulation of various operational conditions – for example, the mechanical response to torsional excitations originating from the driven machine, gearbox, electrical motor or supply system. In addition, transient events, such as short circuits or system startup, can be analyzed.

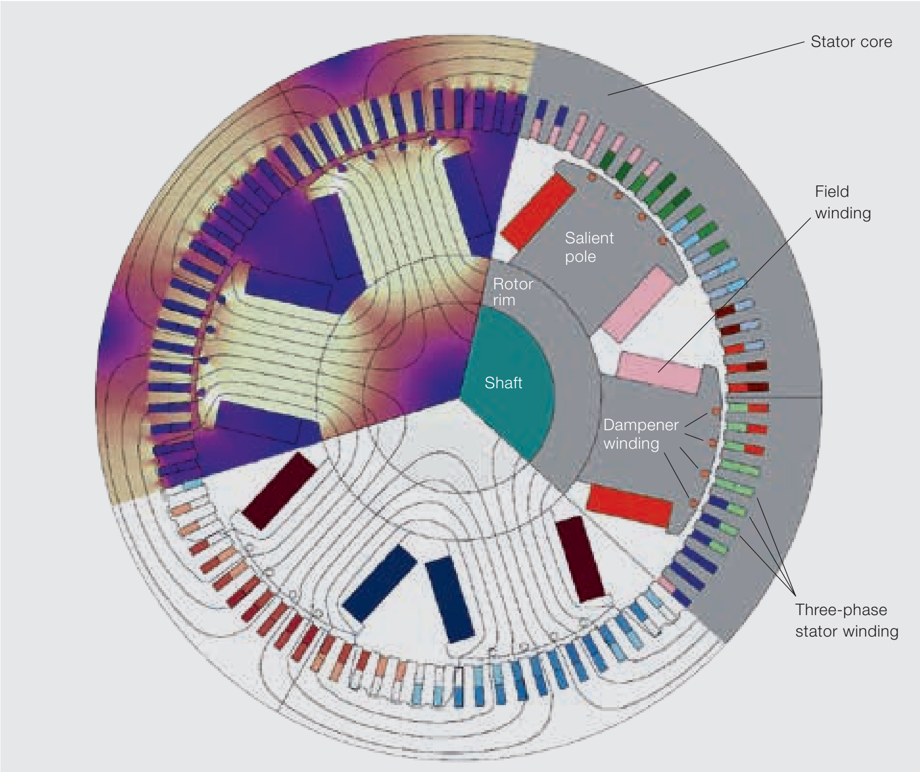
This approach is an excellent way to evaluate electromechanical effects on torsional dynamics and has been used successfully by ABB in some special cases. However, this type of simulation and analysis is computationally too laborious to be used in standard torsional drivetrain design. Further, the system integrators or their consultants do not usually have access to appropriate simulation tools.

Electromagnetic stiffness and damping models

ABB has responded to drivetrain simulation challenges by developing simple, portable models that accurately describe electromagnetic interaction [3]. The key to these models is the calculation of electromagnetic spring (torsional stiffness) and damper coefficients ➔ 4. Both of these coefficients are frequency dependent and can be determined without a mechanical drivetrain model by simulating the motor in the steady-state operation condition. The torsional stiffness is the ratio between the oscillating torque and angular displacement amplitudes, and the damping is the ratio between the torque and velocity amplitudes.

A consensus of common and simple models that accurately describe electromagnetic effects in drivetrains is emerging, though the exact form of these models is still open.

3 Cross-section of a six-pole synchronous high-power motor



In principle, these stiffness and damping ratios can be calculated for one frequency by forcing the rotor to oscillate at that frequency and calculating the oscillation of torque at the same frequency. In practice, this becomes complicated because the rotor and stator slotting generates torque harmonics that may coincide with the frequency under investigation. This interference can be eliminated by calculating a reference analysis with exactly the same parameters but without the rotor oscillation and "subtracting" it. The only drawback of this approach is the large amount of computation needed: Two time-domain simulations with post-processing are required to yield the coefficients for just one frequency at one specified operation condition.

A more effective solution is to apply a spectral method that is based on the impulse excitation. In this approach, the rotor is excited by a forced rotational pulse and the torque response is simulated. After calculating the difference between the results of this simulation and the reference solution, the electromagnetic stiffness and damping coefficients can be determined for a frequency range. This range is dependent on the pulse parameters but it easily covers the frequency range of interest to drivetrain torsional design. Surprisingly, this kind of impulse method can be used for a nonlinear and time-harmonic system – numerous simulations show that the system seems to be linear with respect to the excitation amplitude and, thus, the calculated stiffness and damping coefficients describe behavior during arbitrary torsional oscillation.

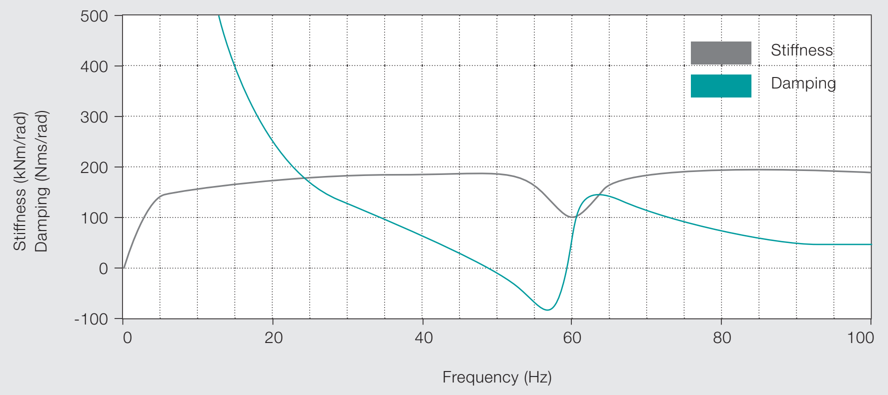
In this way, the large number of simulations previously needed to determine the stiffness and damping coefficients can be replaced by just two.

The electromagnetic stiffness and damping coefficients thus extracted can then be included in the drivetrain torsional analysis. The frequency dependency of these parameters may complicate their inclusion slightly but, in principle, all analysis programs can handle this kind of dependency. Of more concern is the fact that the coefficients are calculated for only one operational condition.

Equivalent circuit model

A more flexible, but slightly less accurate, solution is to apply an equivalent circuit model that handles the electromagnetic effects. At ABB, this approach has been used in drivetrain analysis and design for more than 20 years: A sophisticated in-house software – Simulation of Machine

4 Electromagnetic torsional stiffness and damping – clearly dependent on the vibration frequency – of a 60 Hz / 932 kW induction motor [3]. Note negative damping between 49.7 and 59.4 Hz.



Transients (SMT) – was developed in the early '90s and this has had great success, especially for systems featuring large synchronous motors.

An equivalent circuit model is an analytical motor model described by a limited number of parameters (about 10, in the simplest models). Such models describe the behavior of an electrical machine from the supply voltage entry point all the way through to the resultant shaft torque and speed. They were developed for electrical analysis and design before the advent of computers but are still useful as part of a drivetrain torsional model. The challenges of using them here are related to the coupling of the equivalent circuit model to the mechanical drivetrain model. The former is not a standard component of a typical torsional model and, therefore, its inclusion without source code access or in-depth understanding is challenging. However, it is eminently feasible and this kind of a motor model is often used as a part of a frequency converter control system.

Accuracy is another challenge inherent in equivalent circuit models as they were developed during the pioneering years of electrical machines when model parameters were based on the actual dimensions of critical parts and experimental results. Today, simulation models can be applied to determine model parameters. This approach combines the accuracy of simulation and the simplicity and portability of the equivalent circuit models.

Model role

Today's electromagnetic field simulation models produce accurate information with little effort, but electromagnetic effects are only occasionally included into the torsional design of drivetrain systems. The main reason is, probably, the difficulty of including the effects in a standard calculation program that can be made available to system integrators.

There are various ways to combine the mechanical and electrical parts of the drivetrain torsional models, but a consensus of common and simple models that accurately describe electromagnetic effects in drivetrains is emerging, though the exact form of these models is still open. ABB continues to work in close cooperation with customers and the rotating machines community to refine these models. This development work will make it easier for electromagnetic effects to be included in drivetrain analysis as a matter of course and lead to new, improved drivetrain products.

> The large number of simulations previously needed to determine the stiffness and damping coefficients can be replaced by just two.

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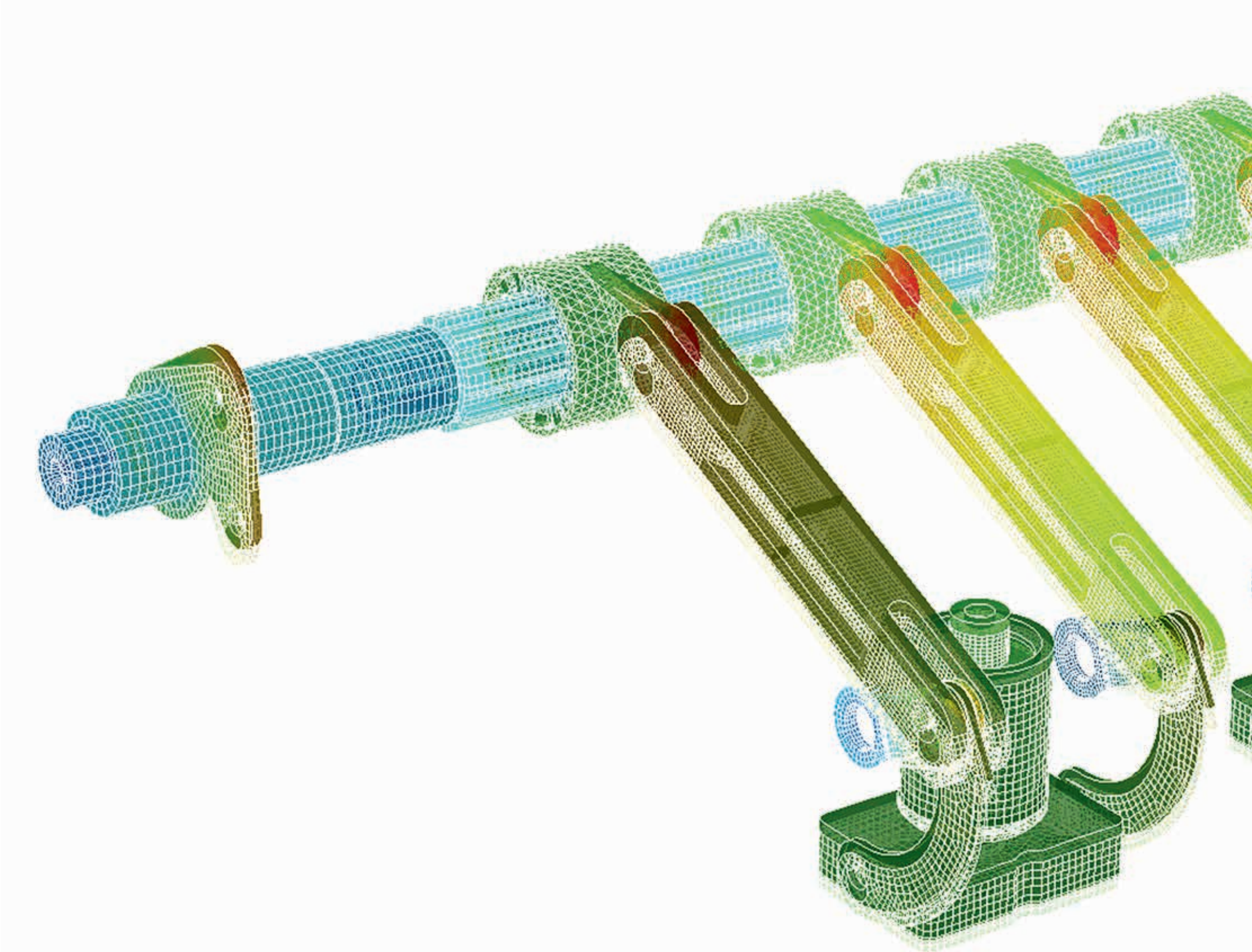


Model matrix

Modularized simulation concepts for breaker analysis and optimization

GRZEGORZ JUSZKIEWICZ, CHRISTIAN SIMONIDIS, GREGOR STENGEL, LUKASZ ZIOMKA, SAMI KOTILAINEN – Computer simulation tools have long been used in product development. Increasingly, engineers are facing situations in which simulations from different physical disciplines must be combined. Medium-voltage and high-voltage circuit breaker development is a good example of this: Mechanical, gas flow, tribological, hydraulic and electromagnetic effects all have to be taken into account during design and test phases and, ideally, each of these should be simulated in concert with the others. Moreover, coil-actuated breakers can be controlled electronically, so the control aspect also has to be woven into the design and analysis of the product. Traditionally, each domain had a dedicated simulation tool and dedicated experts who cooperated and exchanged simulation data and knowledge at appropriate junctures. However, the complexity of modern breaker design demands that these simulation domains be organized inside a structure that guarantees real-time and dynamic transferability, transparency and reusability as well as model object libraries and interfaces that are easy to use.

In the postprocessor, the user can view all predefined field outputs, show or hide part instances, create cross-sections and define custom views.

In today's multinational development environment, simulation tools must be used across disparate organizations by engineers with different levels of expertise. Moreover, they should be utilized in the most efficient manner possible – one in which best practices can be easily captured and repetitive model-building tasks are automated or eliminated. Two main approaches to this are employed at ABB for circuit breaker design.

Tools and environment

The first approach is provided by the breaker simulation toolkit (BST) – a set of user-defined subroutines built into the commercial multibody simulation tool MSC.ADAMS. The subroutines define commonly used circuit-breaker components such as operating mechanisms, linkage components, dampers, etc. The BST components are fully parametric, which enables various design studies to be run, and are easily accessible from the graphical user interface of MSC.ADAMS.

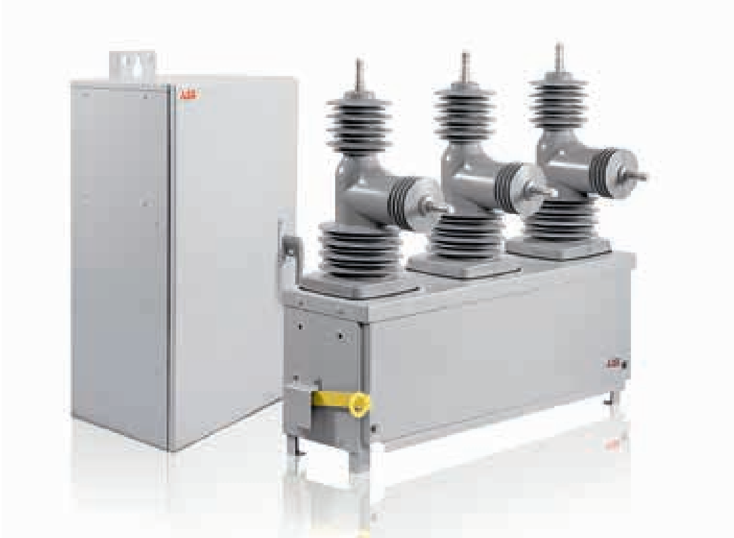
A slightly different approach is taken by the interrupter libraries implemented in the Dymola platform – a commercial modeling and simulation environment based on the open Modelica modeling language. Here, the entire thermodynamic behavior of the interrupting chambers is modeled from standard components and stored in a central library. In this way, all of the development variants are available during the development project and, as the final design is released, it is stored and made available to various external users when necessary. External users cannot change the variants and model encryption protects sensitive information. This approach offers the benefits of a quick devel-

In today's multinational development environment, tools must be used across disparate organizations by engineers with different levels of expertise.

Title picture
To quickly get an insight into the complex physics of breaker behavior, diverse simulation tools have to be harnessed to work together in a structured setup that facilitates tool chaining and runtime variable exchange between the tools. But the interaction of tools that simulate completely different physical domains is a complex matter, so how can it be managed?

An alternative to chaining is the fully coupled approach. Coupling addresses the requirement to have realistic real-time and dynamic interaction of physical domains.

1 The elements of the three-phase ABB Gridshield recloser. The RER620 protection and control unit (bottom right) is standard with the recloser.



opment process while ensuring the same variant of the product is available to all users.

Sometimes it is necessary to have flexibility when handling the components (ie, selected parts of the whole assembly) of the system to be simulated. In the case of MSC.ADAMS or Dymola, component object geometry is represented by a mass point ("lumped mass") with predefined inertia moments and components themselves treated as rigid entities. Simulations based on finite element analysis (FEA) methods then offer accurate calculations of stresses, strains and many other variables for components represented in a discrete way. Interactions between components can be formulated in terms of connector elements and in terms of contact behavior.

Contact modeling is of great importance when there are complex interactions between parts of the assembly – one can predict possible collisions between components and evaluate the maximum contact pressure.

ABAQUS is one example of a commercial FEA package that can provide this flexible modeling of multibody systems. Because ABAQUS represents the system in finite element form, additional effort is required from the user for mesh generation, definition of relations between components, material assignment, load characterization and boundary condition setup. The open-source Python scripting language can be used to automate some of these steps. In addition, sophisticated features of the finite element model can be defined by user subroutines. Besides this, FEA also offers a hybrid method for multibody system modeling whereby some components are represented by rigid bodies and others by flexible ones. This can make calculation times much shorter than in the case of full flexible body modeling.

The tools and environment necessary for complex simulations are thus available. The task remains to organize these in such a way that tools from very different physical domains are made to work in concert to produce the very best simulation results.

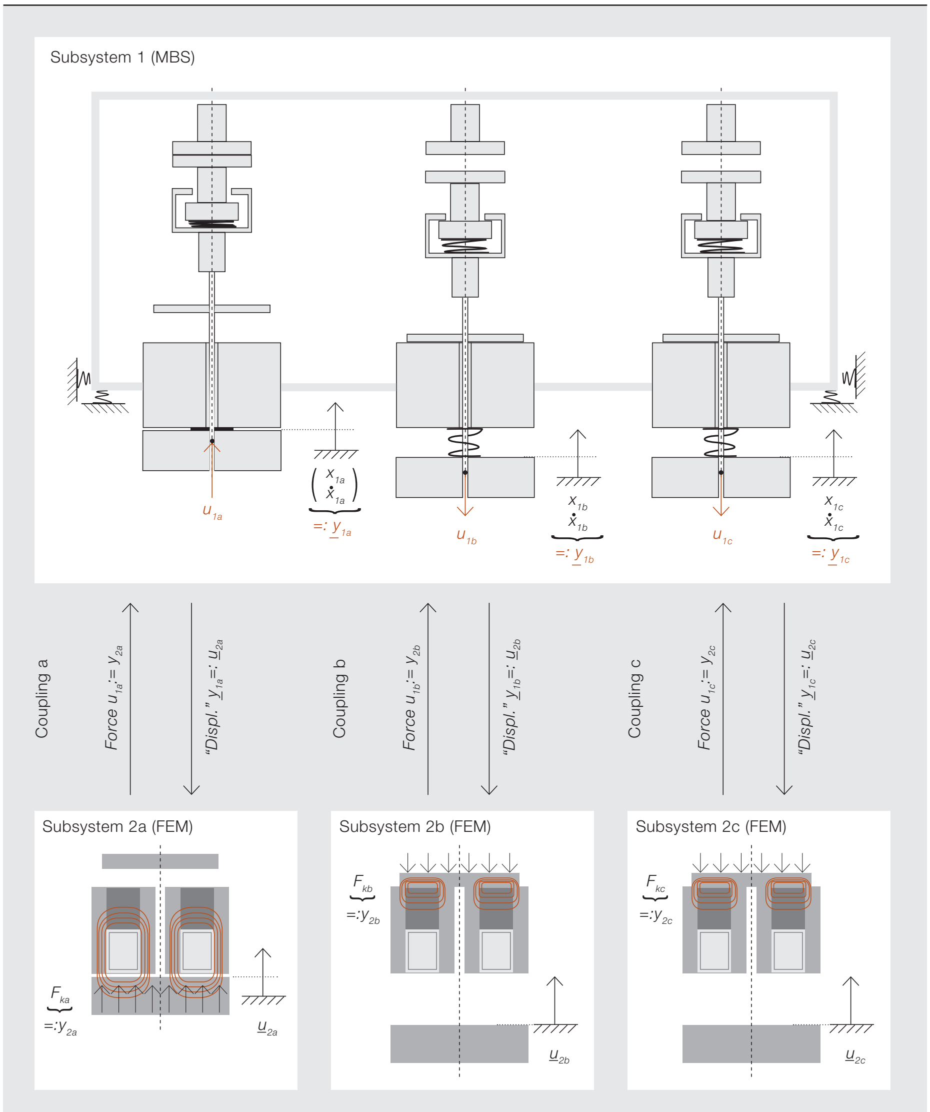
Tool chaining and model coupling

During product development, the output of one simulation can often be used as input to another. This is called tool chaining. In the case of mechanism simulations, results from rigid body calculations (eg, MSC.ADAMS) can be transferred to an FEA package (eg, ABAQUS) so that particular details may be scrutinized. Another example is when output from a thermal simulation is supplied as starting data for a full fluid dynamics simulation.

An alternative to chaining is the fully coupled approach. Coupling addresses the requirement to have realistic real-time and dynamic interaction of physical domains. Two approaches to this are prevalent:

In the first, the overall physical equations are implemented in a single appropriate multiphysics software tool, using realistic models of nonlinear external forces instead of simplifications such as lookup tables.

2 ABB Gridshield Recloser – simulation scenario



During product development, the output of one simulation can often be used as input to another. This is called tool chaining.

In the second, mono-disciplinary submodels are built up in dedicated tools and coupled together in the mathematical sense. The physical-domain-related equations of the submodels are solved by their own particular time-integrator and information related to the state of both systems is exchanged at certain synchronized times. This so-called co-simulation enables the computation of complex physical interactions, facilitates reuse of submodels and efficiently concentrates expert knowledge in particular physical domains.

Coupling environment

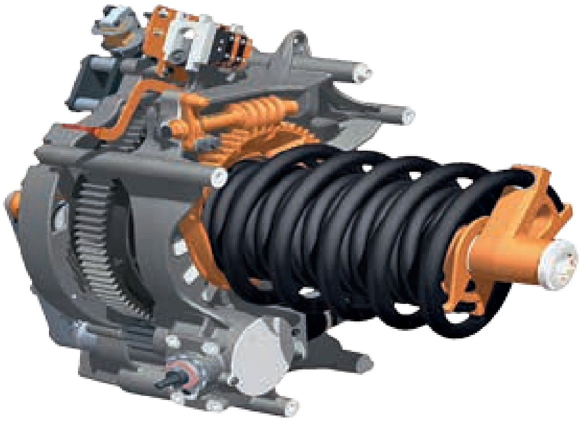
ABB has created a simulation environment that makes use of both in-house and commercially available coupling routines to enable co-simulation between the worlds of multibody mechanics, structural mechanics, fluid dynamics and transient electromagnetics. Analysis of the interaction of magnetic diffusion effects and mechanism dynamics is one particular, and important, tool not widely available in current multiphysics offerings. To compensate for this, ABB has developed an appropriate environment in cooperation with universities to allow the coupling of COMSOL (an FEA package tailored for coupled phenomena) with MSC.ADAMS.

Co-simulation and breaker design

A recent coil-actuated product, the ABB Gridshield® recloser, has been simulated using co-simulation → 1. This simulation scenario involves several subsystems → 2. The electromechanical analysis carried out in this product development provides a good example of coupled simulation.

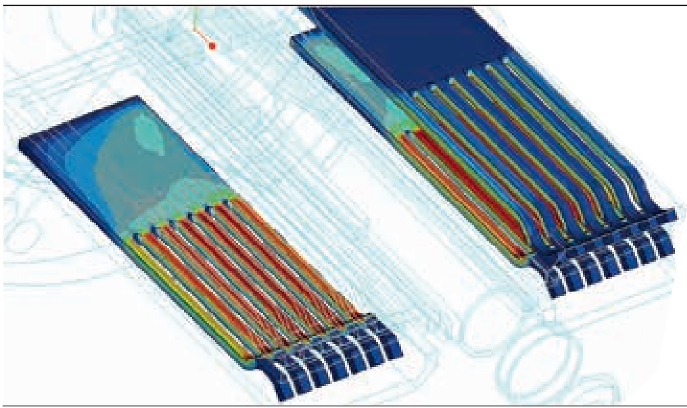
The first step in such an analysis is to evaluate current density and Lorentz force distribution. The second step involves the calculation of stress and displacement of parts subjected to Lorentz forces. Lorentz forces, power losses and current densities can be computed using Simulation Toolbox, an ABB-internal software. For stresses and displacements there are two tools that can be used: the mechanical solver embedded in Simulation Toolbox or ABAQUS. The latter allows customized simulation: More field outputs can be added, nonlinear material properties can be defined and a modal analysis can be performed to check eigenmodes and natural frequencies. Simulation Toolbox uses PTC Creo Simulate as a preprocessor and postprocessor. PTC Creo Simulate allows 3-D virtual prototyping that enables structural and thermal properties of a design to be tested early on in the design process. In the postprocessor, the user can view all predefined field outputs, show or hide part instances, create cross-sections, define custom views and so on.

3 ABB MSD1 drive

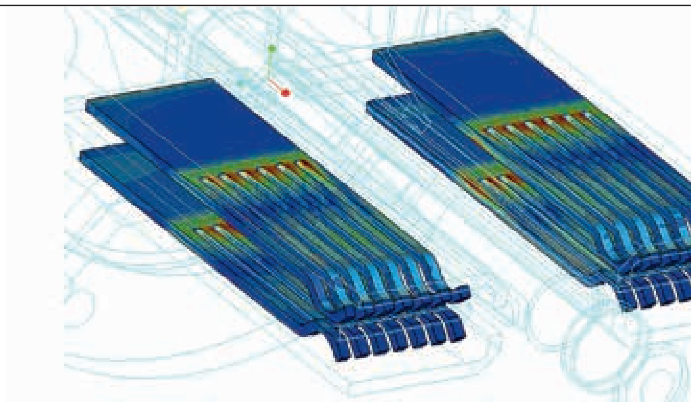


4 ABB MSD1 drive – displacement field view

5 Breaker contact fingers – Lorentz force and stress field view



5a Lorentz force density



5b Stress field distribution

Example – breaker drive

The MSD1 drive is mounted on a high-voltage circuit breaker and is responsible for opening and closing the circuit breaker contact ➔ 3. The energy required to open and close the contact is stored in three springs. Two of the springs are used to close the contact and one (the outer one) to open it. When they are released, the energy stored in the springs causes rotation of the main shaft of the drive. This shaft operates the contact mechanism inside the circuit breaker.

This device (or its components) can be modeled using several different simulation tools (viz., MSC.ADAMS, Dymola, ABAQUS). Moreover, these tools can be coupled together – output from one solver can be used as input to another. The ABAQUS output for a displacement field calculated in this way is shown in ➔ 4.

Example – breaker contact fingers

Another example of co-simulation is found in the electromechanical simulation of the breaker components. The idea of this simulation was to evaluate current and Lorentz force density. Evaluated forces were transferred to an FE (finite element) structural code so the stresses and displacement could be evaluated. An example of current density and stress field distribution is shown in ➔ 5.

Future framework

Modern simulation tools offer a wide range of powerful methods that can be used to solve the complex problems encountered during the development of sophisticated products. Tools that simulate several different physical regimes can be coupled and chained by using externally and internally developed software and plugins. This synergic methodology leverages the strengths of the individual tools and delivers a simulation technique that is much more than the sum of its parts. Importantly, this modular simulation approach produces accurate and useful results within a reasonable calculation time. Work is ongoing to increase the convergence of these simulation tools and to further integrate them into one coherent framework. Thus, they will be even easier to implement and engineers of varying degrees of expertise in different organizations will be able to exploit this synergy to produce even better products.

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Smart outlets for smart phones

Mains outlet with integrated USB connector

SASCHA DEHLEN – The USB interface has rapidly become a very popular global standard that is supported by many commercial enterprises and governmental organizations. So pervasive is this handy connector that the typical household will now have multiple devices that rely on it for data transfer and battery charging: Phones, smartphones, tablets, MP-3 players, digital cameras and satellite navigation devices all sport this ubiquitous connector. However, a problem arises when the time comes to recharge these accessories: Where is the charger? This is often coupled with the dilemma of determining which domestic appliance should then be unplugged to make way for the charger, once found. These problems are done away with by Busch-Jaeger's SCHUKO® mains outlet with integrated USB connector.

1 The Busch-Jaeger SCHUKO USB outlet

2 The Busch-Jaeger USB power supply

In many countries, the SCHUKO mains power outlet on the wall represents a comforting and stable aspect of technology that has remained unchanged for decades while the technology that uses the power it channels has evolved at a dizzying pace. It might seem like a typical mature product that would remain forevermore untouched by further innovation, but Busch-Jaeger has now changed the face, literally, of the domestic power outlet by marrying it with the most popular connector of the past half-century – the universal serial bus (USB) ➔ 1.

This prize-winning innovation does away with the need to have individual transformers and USB cables plugged into household outlets – the USB charging point is simply always there.

Busch-Jaeger has changed the face, literally, of the domestic outlet by marrying it with the most popular connector of the past half-century – the USB.

Devices can now be recharged conveniently and without unplugging domestic appliances. The flush-mounted USB SCHUKO outlets deliver up to 700 mA charging current and feature child protection. Because the form factor matches existing SCHUKO outlets exactly, upgrading to the new USB outlet is easy.

Two further innovations

The company has developed two companion USB charging products for the USB SCHUKO outlet – a USB power supply and a USB charging station. These are also flush-mounted units.

The Busch-Jaeger USB power supply provides two USB connectors for charging purposes ➔ 2. It uses the standard cover found on TAE telephone outlets and users can configure either two 700 mA connectors or one 1,400 mA connector depending on the charging requirements of the device attached (tablets, for instance, can be power-hungry devices.)

Title picture
Innovation is at its most dramatic when it touches things that have remained unchanged for decades. Equipping the humble domestic power outlet with a USB charging facility is a good example.

3 The Busch-Jaeger USB charging station

With the Busch-Jaeger USB charging station, charging capability is supplied via a flexible cable with a micro-USB connector that can deliver up to 1,400 mA of charging current. The micro-USB interface has been chosen as it is the most popular connector standard globally and it also conforms to EU standards. The charging station also provides a convenient holder for the smartphone that is to be charged → 3. The holder has an antislip surface to keep the phone secure should it vibrate.

Awards

Several international prizes have been conferred on the Busch-Jaeger SCHUKO USB outlet: it won the Dutch 2013 Rexel Innovation Prize and the prestigious ETOP Innovation Award – a distinction bestowed by the exhibition organizer VNU Exhibitions Europe and the Dutch electrical organization "Federatie Elektrotechniek" at the 2013 Elektrotechniek trade fair in Utrecht.

Further, the SCHUKO USB outlet received the Audience Choice Award in September 2013 at the design pavilion of the IFA trade fair in Berlin → 4. This award aims to raise the profile of design and usability for both users and manufacturers.

4 IFA Audience choice award

Busch-Jaeger SCHUKO USB outlet was recipient of the Audience Choice Award in September 2013 at the design pavilion of the IFA trade fair.

Unusually for an ABB or Busch-Jaeger product, and as an indication of its wide appeal, the SCHUKO USB outlet recently had its own prime-time television commercial spot on German national television.

The USB connector itself is not only becoming ubiquitous, it is being developed further: A reversible version is planned (the current, nonreversible, design was chosen for economy) and a next-generation USB interface should be able to deliver 100 W – replacing power cords in some applications. All this means that USB connectivity will become even more prevalent in the domestic setting and the integration of USB technology into household appliances and infrastructure will become not just a matter of convenience, but one of necessity. The SCHUKO USB outlet is the first step in that direction.

Because the form factor matches existing SCHUKO outlets exactly, upgrading to the new USB outlet is easy.

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Power player

ABB's PCS100 RPC does more than just compensate reactive power

SOPHIE BENSON-WARNER – For some manufacturers, it can be a headache if their power supply fails or suffers quality degradation. For others, however, such power events can herald a major catastrophe, resulting in huge recovery costs and expensive production downtime. ABB's Reactive Power Conditioner is designed to mitigate most common supply voltage problems caused by reactive power, harmonics, fast changing loads, voltage drop, poor power factor and so on. In combination with an appropriate uninterruptible power supply, the Reactive Power Conditioner can provide a comprehensive power quality solution for industrial, commercial and renewable energy applications.

Title picture
Power supply degradation is best avoided when possible. ABB's PCS100 Reactive Power Conditioner helps maintain a supply of high-quality power to critical loads, like this water pumping station.

1 Most of society's industry and infrastructure is dependent on a constant supply of clean, high-quality power.

In the home, it can be annoying when far-off power grid events cause the lights to flicker, or even cause equipment to temporarily switch off. For industry, the effects can be much more dramatic: If a production line has to stop, it has to be restarted and, for some industries, this can be a complicated and very expensive exercise. Equally, utilities, such as gas, water and electricity providers, are very dependent on a stable power supply, as are a host of other entities, such as office complexes, transportation systems (trains, airports, etc.) and ports → 1. In the industrial setting, detrimental power events can be self-generated – by welding equipment, arc furnaces or fast transients from embedded generation sources such as photovoltaic, for instance. It is best, then, to invest in appropriate equipment and ensure a constant supply of clean, high-quality power. ABB's PCS100 Reactive Power Conditioner (RPC) tackles most of the power quality problems found in industry.

The PCS100 RPC is rated for applications from 100 kVA to 2,000 kVA and uses high-speed IGBT inverter technology to control reactive power flow into the AC network.

Power protection

ABB has a variety of power protection products and the PCS100 Reactive Power Conditioner (RPC) is the latest addition to this portfolio → 2. Specifically designed for industrial and commercial applications, the PCS100 is able to respond instantly to power quality events, while providing continuous reactive power correction → 3.

Power problems can manifest themselves as power factor issues, inrush-generated sags, voltage imbalance or voltages outside regulatory requirements (a particular problem for direct online motors) and harmonics. These can result in financial penalties and costly electrical equipment malfunctions if left uncorrected. Although the PCS100 RPC's prime role is to condition current, by injecting reactive current into the circuit to stabilize the voltage, the PCS100 RPC can pro-

2 The ABB PCS100 RPC

Power problems can result in financial penalties and costly electrical equipment malfunctions if left uncorrected.

vide a very cost-effective solution to these problems. Because the PCS100 RPC conditions the current drawn by the customer's load, it fits well with ABB's other products in the PCS100 family, such as the PCS100 UPS-I uninterruptible power supply (UPS) and the PCS100 Active Voltage Conditioner (AVC), which provide power supply to critical loads and condition voltage, respectively [1].

The PCS100 RPC is rated for applications from 100 kVA to 2,000 kVA and uses high-speed insulated-gate bipolar transistor (IGBT) inverter technology to control reactive power flow into the AC network. By injecting capacitive or reactive current at different frequencies and phase angles, the PCS100 RPC efficiently and reliably provides:

– Fast dynamic reactive power
– Unity power factor
– Correction of current imbalance
– Harmonic cancellation

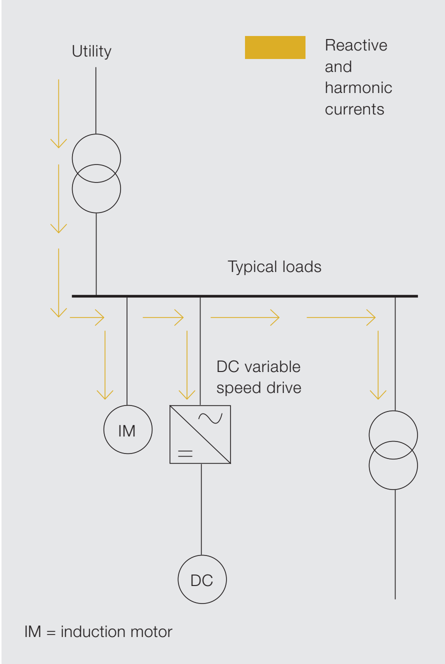
The inverter technology employed means the compensation is stepless, unlike many other solutions. This minimizes disturbances and ensures seamless power conditioning.

Modularity

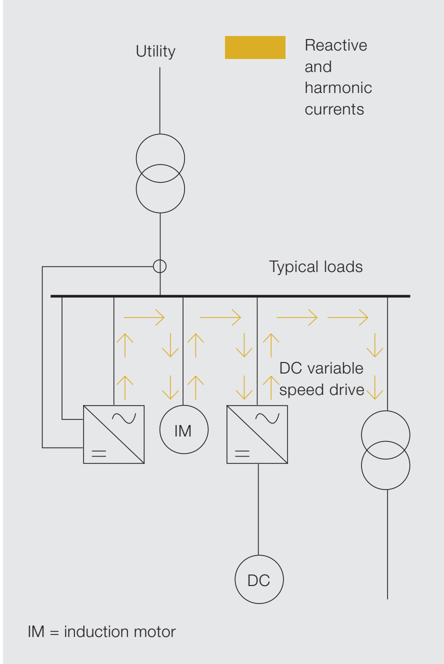
A complete range of cabinets for the PCS100 RPC is available. They are all suitable for direct connection to typical low-voltage supplies (380 to 480 V) → 4. The devices are rated from 100 kVAr to several MVAr. Combined with the PCS100 UPS-I and the PCS100 AVC, the PCS100 RPC can be applied to a wide range of situations, from computer

The highly reliable modular redundant designs mean the system is scalable and can be easily expanded as power needs grow.

3 ABB PCS100 RPC schematic



3a Without PCS100 RPC



3b With PCS100 RPC

room backup to large data centers and complete industrial plant protection. The highly reliable modular redundant design means the system is scalable and can be easily expanded as power needs grow. In addition, if one of the power modules fails, the system will not trip, but will continue to operate at reduced capacity. Because the granularity is small, the manufacturer can get full redundancy at very low cost. This level of reliability at such low cost is unique in the industry.

RPC plus UPS

A comprehensive power assurance package can be created by combining the ABB PCS100 RPC with an ABB PCS100 UPS-I. Precisely this has been done for one particular customer to help protect its critical polyimide film manufacturing line.

Polyimide materials are lightweight, flexible and resistant to heat and chemicals. They are typically used for flexible printed circuit boards in items such as telecommunication devices, wireless suspensions for hard disk drives and optical pickups. ABB's customer is a critical supplier to the electronics world and a power outage in the manufacturing process would result in significant recovery costs and production downtime as well damage to the company's reputation.

The inverter technology employed means the compensation is stepless, unlike many other solutions. This minimizes disturbances and ensures seamless power conditioning.

The power protection package provided by the two PCS100 products enables outages, sags and swells to be eliminated (via a 1,050 kVA PCS100 UPS-I), while at the same time increasing the power factor of the load above 0.90 (via a 323 kVAr PCS100 RPC). In addition to dynamic power factor control, the PCS100 RPC also provides filtering of low-order harmonics, further improving power quality. This value-added concept was a key factor as protection of vital assets was essential to continuous output.

4 The ABB PCS100 RPC cabinet interior

A comprehensive power assurance package can be created by combining the ABB PCS100 RPC with an ABB PCS100 UPS-I.

This turnkey solution means that if a power outage occurred, the PCS100 UPS-I would disconnect the load from the utility and supply the manufacturing line with full power for 5 min. Simultaneously, the PCS100 RPC would provide power factor control above 0.90. The customer's expectations were that, should a power outage occur, the UPS-I would supply power to the load of 1,000 kVA. ABB's PCS100 UPS-I is able to go beyond that expectation and supply 1,050 kVA to protect the load in the event of a shutdown.

The PCS100 UPS-I includes a high-speed static switch, meaning that the transfer to power stabilization mode occurs very quickly. After further evaluations were undertaken, the company found that no competing products could provide this. The final deciding factor related to system efficiency as the manufacturer was able to save a large sum on air conditioning requirements due to low heat loss from the PCS100 UPS-I. The ABB PCS100 RPC itself has an efficiency of 99 percent. It also has a small footprint and is thus a good option when real estate is scarce or expensive.

The modular and scalable architecture of the ABB PCS100 RPC and its compatibility with the other members of the ABB power protection family, as well as its success in combating common industrial power problems, has already resulted in significant success in a range of power protection applications. For example, a 100 kVar RPC is helping to improve the electrical drive power quality of Wellington's iconic cable cars. This project on New Zealand's capital city's funicular railway includes some firsts for ABB: As well as being the first PCS100 installed in New Zealand, it is the also the first in the public transportation industry globally. It is also the smallest footprint PCS100 product ever built.

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In harmony

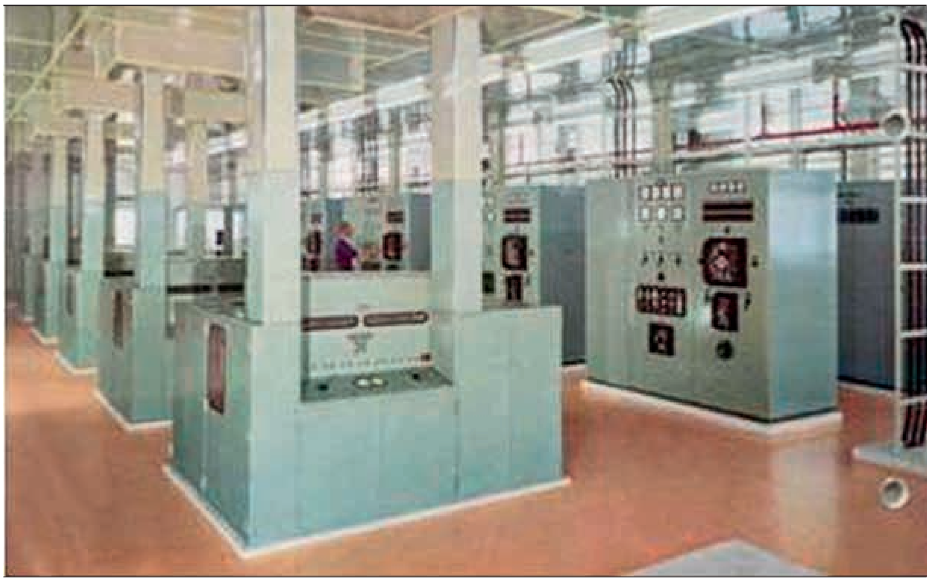
Looking back on a fruitful history of co-development of high power rectifiers and semiconductors

SHRIPAD TAMBE, RAJESH PAI – Although most electrical energy in the world is generated, transmitted and distributed in AC form, at utilization level many applications need DC. These include – but are far from limited to – electrolysis, steel making, traction and plasma torches. Power electronics support these applications in a reliable, dependable, economical and efficient manner. High power rectifier (HPR) development has been symbiotically linked to progress in semiconductor technology: The history of the two are thus best studied in conjunction. Both ABB's HPR and semiconductor technologies have evolved over a number of decades while achieving dazzling levels of technological progress. Today ratings in the hundreds of megawatts – unthinkable a few decades ago – are commonplace. In issue 2/2013, *ABB Review* visited the company's 100-year history of power electronics by looking at semiconductor technology and manufacturing. As part of the same celebration, the present article takes a different approach: It explores the development of power electronics from the perspective of ABB's HPR business.

Title picture
High power rectifiers have been an important part of smelting plants for many decades, and continue to fulfill this role today. This 2008 view shows the Boliden copper smelter (Sweden).

1 Mercury Arc Rectifier

2 Contact rectifier



The journey of invention and innovation that has been pursued in the domain of semiconductors for high power rectifier applications over the past decades from the origins of the technology to the devices available today is a remarkable one. And this progress is visible not only in datasheet numbers such as megawatts and kiloamps, but also in terms of safety and reliability, even under extreme operating or environmental conditions.

The primary goals of the BBC / ABB rectifier division has always been to build safe and efficient rectifier systems. The safety of the equipment but most importantly the safety of the people working with the equipment has been at the nucleus of all efforts and developments.

The origins of power electronics

Although developments in the field of power electronics over the last four decades years are symbiotically linked to progress in power semiconductors, ABB's predecessor companies were already active in power conversion long before semiconductor technology was commercially harnessed or even understood[1].

Mercury vapor rectifiers

Early rectifiers (starting around 100 years ago) used mercury vapor devices. They relied on the property of mercury vapor to block one polarity of AC current → 1.

Contact rectifier

AC to DC conversion was achieved by contact rectifiers. This technology supported conversion up to several kiloamps → 2.

The entry of semiconductors into rectifiers

The development of robust and high power semiconductors sparked a revolutionary change in the industry and created opportunities for numerous new applications. The elimination of the risks associated with mercury arc rectifiers and the high maintenance effort associated with contact rectifiers led to a rapid adoption of the new technology.

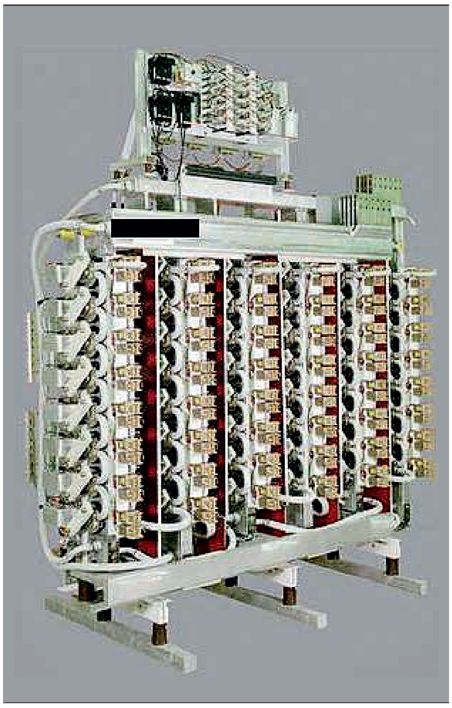
The ease with which semiconductors could be handled, with which heat could be dissipated, and with which series or parallel connection of devices could be achieved made them an indispensable part of countless applications.

BBC developed its first diode rectifier in 1956. This breakthrough was followed by the introduction of thyristors in 1960. In the following decade BBC developed pig tile diodes (glass and ceramic cylinder with bolts and flat bottom) for use in high power rectifier applications.

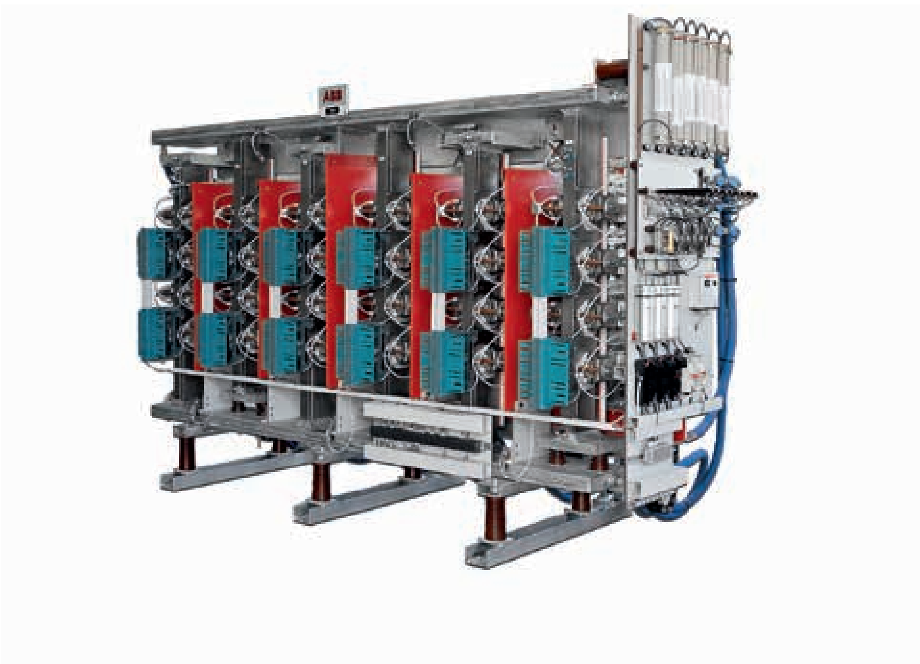
Footnote

1 See also "From mercury arc to hybrid breaker: 100 years in power electronics" in *ABB Review* 2/2013 pages 70–78.

3 Two inch thyristor rectifier



4 Four inch thyristor rectifier



The 1970s saw progress in wafer technology in semiconductor manufacturing and the subsequent development of 2" and 3" diodes and thyristors. These were the basis of a milestone breakthrough: BBC's development of the first diode rectifier plant with a DC current of more than 100 kA → 3.

Today ABB builds rectifiers delivering up to 200 kA. This is possible due to the 4" diodes and thyristors → 4 that are available with:
- Various blocking voltages
- Inbuilt explosion protection
- Low and consistent forward voltage drop (devices available in narrow band) for large rectifier units with 16 or more semiconductors in parallel.

Role of cooling medium

Despite the numerous advantages that semiconductors offered, it was the advent of the "press-packed" construction that proved to be the primary breakthrough to widespread use in high power applications. The main advantage of this construction was that it was highly efficient at conducting heat away from the silicon (heat being the main limiting factor of semiconductor performance and also the main cause of failure in operation).

The development of high power semiconductors and their applications is intrinsically linked with the development of the area cooling methodologies. This journey started with natural air cooled systems and progressed to using forced air cooled systems.

A better and more reliable heat transfer helps secure a longer life cycle of the power conversion equipment

As current ratings increased, oil cooled systems were developed. As ratings rose further, the physical properties of oil increasingly became a challenge (namely its inflammable nature and changing viscosity). These physical shortcomings of oil as a cooling medium were banished with the introduction of water cooled and de-ionised water cooled systems. Today systems can be built with single unit delivering up to 200 MW.

Semiconductors: "The Heart of the Rectifier"

The semiconductor is one of the fundamental building blocks of today's high power rectifier systems. The matching of the semiconductor device (thyristor or diode) and the suitable fuse with the application depends on various factors such as:

The primary goals of the BBC / ABB rectifier division has always been to build safe and efficient rectifier systems.

5 The RectiCal tool

RectiCal is equipped with algorithms, simulations and a database of various semiconductors and fuses that are validated by laboratory testing and site measurements. Rectical helps determine the:

- Size of the transformer
- Size of the rectifier including:
  - Semiconductor and fuse types
  - Number of parallel elements
  - Overload capability of the rectifier
  - Rectifier losses, ie, semiconductor and fuse loss
  - Cooling system requirement

- The rectifier application (aluminum smelting, copper or zinc electrolysis, DC electric arc furnace etc.)
- Rectifier output voltage and current
- Environmental conditions
- Grid conditions specially short circuit capacity
- Duty class and overload ratings

ABB's engineers are supported by a proprietary software tool called RectCal to determine the optimum sizing of the rectifier including selection of the semiconductors and fuses ➔ 5.

Life cycle and efficiency

Investment decisions are taken considering return on investment (ROI). Operational expenses are very important for economic viability. Most of the processes that ABB rectifiers serve have long life cycles. Hence purchasing decisions should not be based on the initial acquisition cost alone, but also on life-cycle costs.

Energy loss (or efficiency) is an important factor in regard to both operational expenses and satisfying environmental concerns and requirements.

The lifetime of the equipment and performance of the semiconductor can be greatly enhanced by the selection of appropriate cooling, mounting arrangements, contact stability between the surfaces transferring heat, current distribution and protection.

ABB has, for more than 80 years, been working to achieve longer equipment lifecycles coupled with high operational efficiency. The company has identified the following key issues as having a significant impact on the lifetime and efficiency of our products.

Mechanical assembly

The mechanical assembly that holds the semiconductors in place together with the heat sinks is designed to maintain a high pressure contact in order to secure a high degree of heat dissipation. A better, more reliable heat transfer helps to secure a longer life cycle of the power conversion equipment.

Current distribution

The cost optimization of a rectifier system requires a precise determination of the required number of semiconductors. For this, the current distribution through the semiconductor has to be resolved accurately. Such understanding of the converter not only optimizes cost but also helps better understand losses and supports the design of cooling system.

Protection

The risk of asset impairment can be minimized by implementing reliable protection against transient overloads and by isolating faulty semiconductors. This translates to longer life cycles. Even in the event of a semiconductor failure, containment and redundancy strategies mean there is usually only a minimum of inconvenience to the plant and often no damage to the rest of the equipment.

Explosion ring

ABB has patented technology that eliminates any kind of plasma spread in the event of semiconductor damage. Many incidents that could otherwise pose a risk of asset impairment are confined to the location of the damaged component. The explosion ring has a significant effect on the length equipment's life cycle.

Most of the processes that ABB rectifiers serve have long life cycles. Hence purchasing decisions should not be based on the initial acquisition cost alone, but also on life-cycle costs.

OVP (overvoltage protection)

One of the most common causes of semiconductor failure is voltage stress beyond acceptable limits. Harmful voltage transients often originate outside of the rectifier system. ABB's system design tools make it possible to provide very effective OVP considering various network aspects, process aspects as well as circuit breakers.

Fuse and semiconductor testing for explosion

Safe isolation of defective semiconductors can be achieved through blowing the series element fuse before the semiconductor reaches a state in which it can cause mechanical damage to itself and its surroundings. The demands on fuses in such applications are high. They need to be effective while consuming a minimum of energy as well as possessing sufficient body strength to withstand the heat generated during the fault. The withstand capability of ABB's semiconductor and fuse combinations are tested under the most sever conditions at ABB's power laboratory in Baden Switzerland.

All of these factors contribute towards achieving longer life cycles and safer operating conditions, and thus support customers in their quest for higher productivity.

Losses and their significance.

Losses in rectifier systems are mainly generated by the semiconductors and fuses. Fuse losses tend to be copper losses, but in the case of semiconductors the situation is different. Some semiconductor losses are proportional to current while others vary in proportion to the square of the current.

$P = I_t \cdot V_t + I^2 R_t$

I = Current through the semiconductor

V_t = Forward voltage drop across the semiconductor

R_t is the equivalent forward conduction resistance of the semiconductor.

Lower losses mean higher efficiency, which means lower operating expenses.

High voltage rectifiers (2,000 V_{DC})

Economy drives technology. Higher efficiency means better economic viability. It is shown that rectifier systems with higher voltages are more efficient than systems delivering the same power output using lower voltages. The reason for this is the fact that major losses increase with the square of the current and only proportionally to the voltage. ABB's reliable semiconductor technology with its capability to deal comfortably with higher voltages enabled the development of 2000 VDC rectifiers. This enabled HPR to offer significant improvements in operating efficiency through operation at higher voltages.

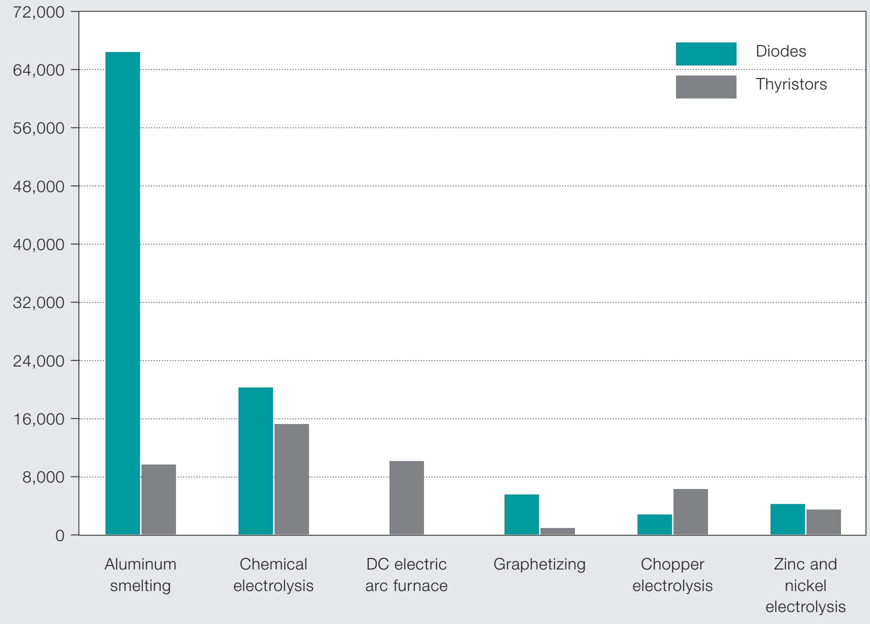
Milestone projects and change in trends

ABB is a technology leader in power electronics in general and in rectifier systems in particular. On its path of development, ABB achieved many milestones. The history of power electronics started with mercury arc rectifiers for research and industrial applications between 1913 and 1925. ABB's predecessor companies built the first HVDC link (1939) and the first commercial HVDC link (1954). In the late 50s, the companies that today make up ABB helped form the basis of today's diode and thyristor semiconductors.

In the journey of semiconductor development, around 1960 BBC developed contact rectifiers capable of up to 6 kA, which was considered a high current rectifier in that era. Rectifier ratings significantly increased between 1967 and 1980 with the emergence of what we now consider as high current and high voltage diodes. Between 1970 and 1980 converters for higher frequency applications (medium frequency heating and melting) and for HVDC established their own niche. These are just selected achievements from among the countless milestones spanning many fields of application. Over the years, ABB was behind the lion's share of breakthroughs in rectifiers for aluminum electrolysis and DC arc furnace applications.

The diode is the preferred semiconductor of the aluminum industry due to its simplicity of controls compared to thyristor-based systems.

6 Semiconductor usage in various HPR applications



100 years of power electronics

ABB's HPR group has been one of the bulk consumers of power semiconductors in ABB, and is proud to be part of the company's 100 year journey. Semiconductors have been used in HPR applications since the 1960s and the quantity of semiconductors used in different applications is testament to the significance of semiconductors to this area of activity → 6.

Aluminum smelting is one of the biggest contributors for the following reasons:
- Big rectifier systems with a large number of semiconductors in parallel
- Number of rectifier systems delivered and widespread and growing demand for aluminum
- Overload and redundancy requirements

The diode is the preferred semiconductor of the aluminum industry due to its simplicity of controls compared to thyristor-based systems. The development of diodes from 2" to 4" and the increase in blocking voltages helped further establish their usage.

Thyristors play an important role in building rectifiers for highly dynamic and demanding loads such as DC electric arc furnaces. Non aluminum electrolysis applications such as of chlorine, copper and zinc mostly employ thyristor-based rectifier systems for efficiency and controllability reasons.

Built for safety

Besides performance and reliability, safe operation has always been at the forefront of ABB's activities in power electronics. This covers the safety of people working with or near the equipment, as well as the protection of the equipment and adjacent installations. HPRs are designed to fulfill high reliability and safety demands, and where they do fail, they are designed to do so in the safest manner possible.

A technology that performs

Semiconductor elements (diodes or thyristors) play a vital role in the building of efficient, robust and reliable high-power rectifiers. As process technology progressed through the years, semiconductors were developed to meet the ever more demanding requirements of the rectifiers. The availability of larger size (4" and 5") discs with increased blocking voltages (4.2 kV, 6.5 kV) make very high power densities possible today.

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Further reading
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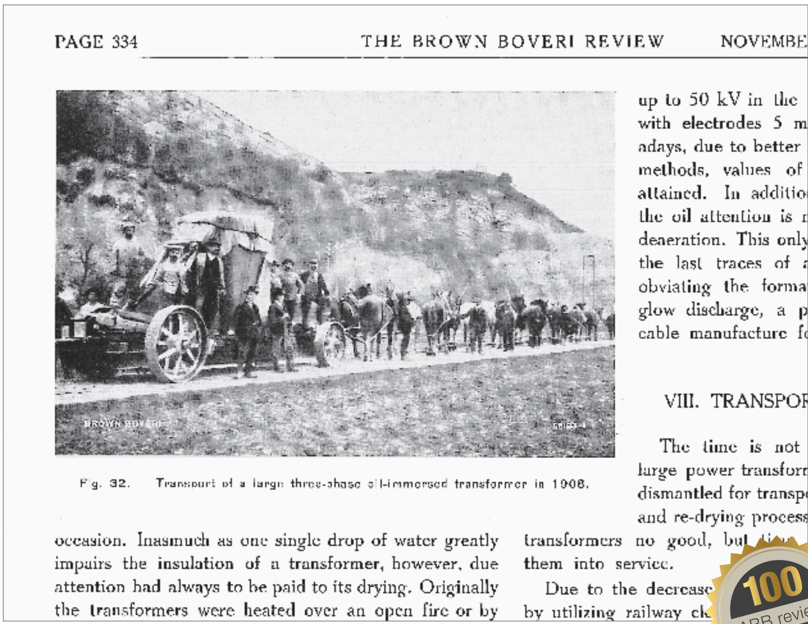

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Fig. 32. Transport of a large three-phase oil-immersed transformer in 1908.

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VIII. TRANSPOR

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transformers no good, but
them into service.

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Preview 2|14

100 years of history

In July of 1914, ABB's predecessor company, BBC, published the first edition of *BBC Review*. Rebranded *ABB Review* in 1988, the journal can proudly claim to have been in continuous production throughout its 100 years, making it one of the oldest entities in uninterrupted existence within the company today.

ABB Review 2/2014 will delve into its archives and rediscover a treasure trove of innovation, ranging from quaint and curious ideas to the origins of many of the technologies and product lines that form the backbone of ABB's business today.

On the occasion of its anniversary, *ABB Review* is also seeking comments and input from readers. Any reader wishing to share memories or insights for the anniversary is invited to contact the chief editor at *andreas.moglestue@ch.abb.com*.

ABB Review is not the only part of the company to be looking back on its history this year. The first commercial HVDC link was completed 60 years ago, and the first ABB robot was launched 40 years ago. *ABB Review* will also mark these anniversaries.

ABB Review on the tablet

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