ABB review
2|13
The corporate technical journal



# Breakthrough technology


Construction of the Atatürk Dam on the Euphrates in Turkey was completed in 1993. Its 817 $km^2$ reservoir can hold 48.7 $km^3$ of water. ABB supplied the eight 300 MW generators, and recently modernized their governors and excitation systems as well as installing a new SCADA system with remote access as well as System 800xA for automation. This page shows the giant powerhouse with the excitation systems located above the vertically mounted turbine/generators (the covers of which can be seen on the floor). The front cover of this magazine shows the Sorgenia Bertonico-Turano Lodigiano combined-cycle plant in Italy, for which ABB supplied the Symphony Plus control system.

Contents

Editorial

# Breakthrough technology

**Prith Banerjee**

**Dear Reader,**

Switches are the essence of virtually every electrical or electronic system. Ranging from the integrated logics of microprocessors in control systems to the massive breakers that control the grid, switching devices underpin almost all of ABB's activities, and indeed technology in general. ABB is continuously seeking to push the envelope of switching capability and thus enable new applications. In many cases this may be about advancing the limits of existing applications. Occasionally entirely new and disruptive "game-changing" breakthroughs redefine the market. The hybrid DC breaker is very much in the latter category.

ABB has for decades been a pioneer of high-voltage DC (HVDC), permitting the transmission of power at low losses over long distances and with high controllability. Moving beyond individual standalone transmission lines, the company believes the backbone of tomorrow's power grid will be an HVDC network. Similarly to AC, a DC grid requires breakers – for example, to be able to isolate individual sections safely in the event of a disturbance without shutting down the entire system. There are, however, significant differences between interrupting AC and DC that cannot be overcome by scaling or adapting existing AC solutions. ABB has overcome these challenges with a hybrid breaker – hybrid because it uses both conventional switching technology and semiconductors. This technology has recently been recognized by the MIT Technology Review as one of top 10 innovations of 2012. The hybrid breaker is the topic of the lead article of this edition of *ABB Review*.

While on the topic of switches, this edition presents a variety of other switching articles, spanning different applications and power ranges – from high-voltage AC to motor control, and even ABB's new semiconductor device: the BIGT, one of whose applications is in the above hybrid breaker. Continuing with the topic of switching and its applications, a history article looks back on the company's 100 year involvement in power electronics. The focus is mainly on the switching devices themselves. A discussion of the applications is planned for an upcoming issue.

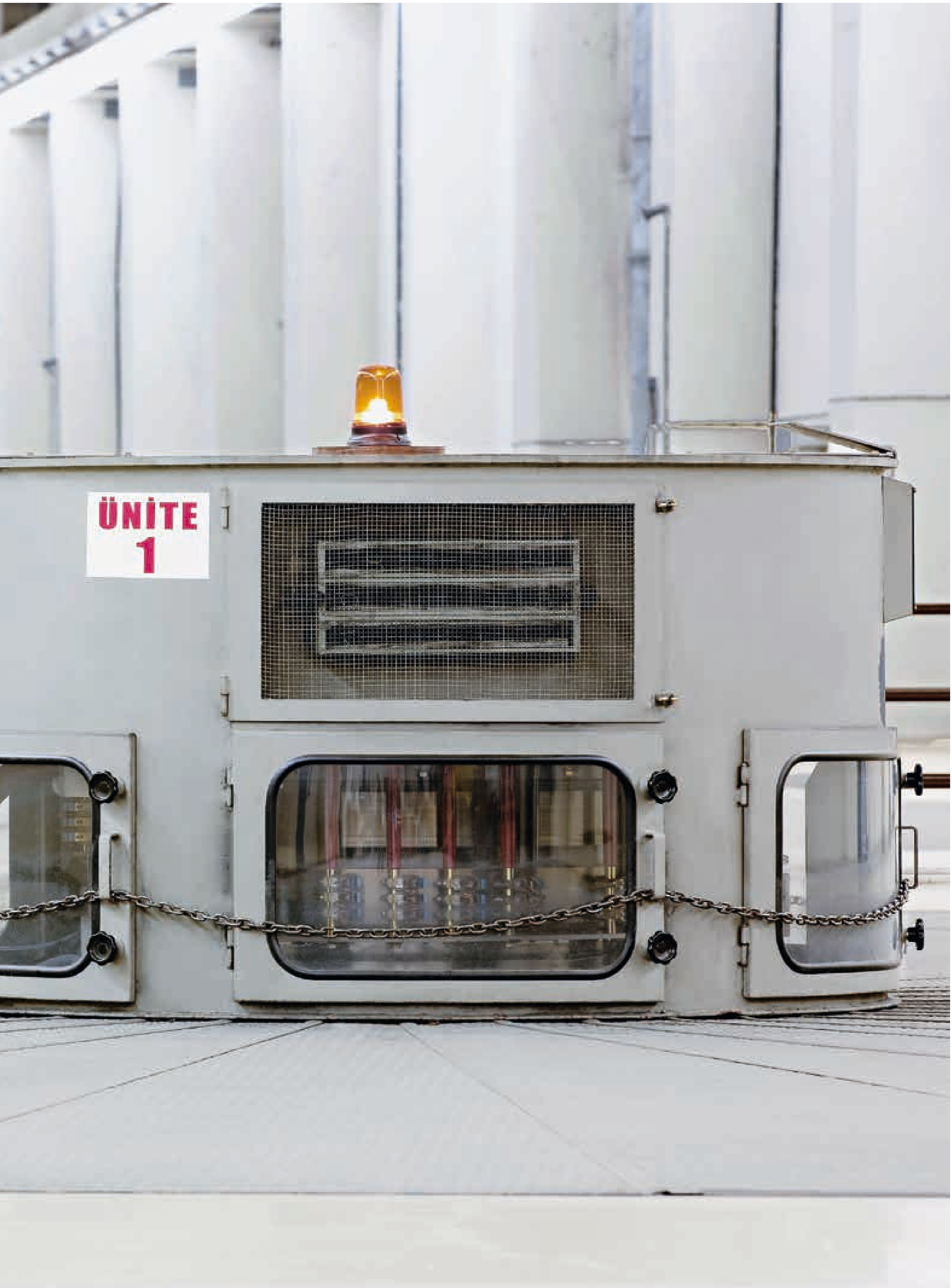
Moving onto other topics, this issue of *ABB Review* has a subsection on mining, presenting a selection of ABB's contributions in this field. Further articles from across the board of the company's activities look at heavy-lifting vessesl, data centers, the simulation of large plants and maintenance planning.

But it is not just electrical current that is being switched. Starting with this issue, some changes are coming over this journal itself. Readers in languages other than English may notice its name has changed to *ABB Review*, creating a uniform identity and recognition across all languages used. Another novelty for those who read the journal in electronic form is an email alert being launched to ensure they never miss an issue (see inside-back cover to sign up). Further changes will be announced in upcoming issues. Despite this development in form and presentation, *ABB Review* remains committed to its high standards of content.

Finally, as my tenure as chief technology officer at ABB comes to an end, I would like to say goodbye to all readers, trusting that you will continue to follow the company's technology advancements through *ABB Review*.

Enjoy your reading!

Prith Banerjee
Chief Technology Officer
ABB Ltd.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JibPLUS


# Break-through!

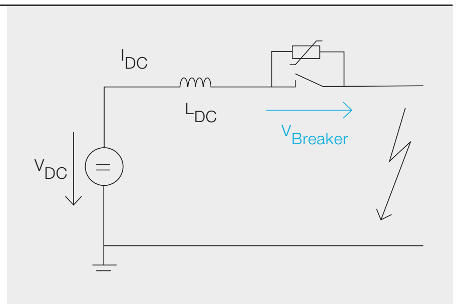
## ABB's hybrid HVDC breaker, an innovation breakthrough enabling reliable HVDC grids

MAGNUS CALLAVIK, ANDERS BLOMBERG, JÜRGEN HÄFNER, BJÖRN JACOBSON –
ABB and its predecessor companies pioneered HVDC (high-voltage direct current) technology, permitting low loss transmission of power over long distances. All HVDC lines realized so far have been point-to-point links. The scope of application of the technology could be greatly increased if lines could be built with more than two terminals, enabling them to develop into HVDC grids. However, the absence of a suitable breaker for the required voltages and speeds and with acceptable losses has hitherto prevented the advent of such topologies for HVDC. All this has changed with the launch of ABB's new HVDC breaker.

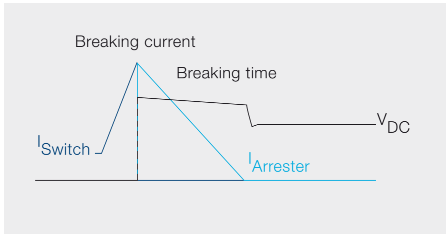
**Title picture**
ABB's hybrid circuit breaker is one of the greatest innovations in the company's history. Finally DC grids can become a reality.

**1 Representation of an HVDC grid and principle of HVDC breakers**

1a Blue dots represent converter stations in HVDC grid.




1b HVDC breaker




1c Principle of operation

Compared to high-voltage AC grids, active power conduction losses on HVDC lines are relatively low and losses related to reactive power are zero, making HVDC grids an attractive proposition for transmission over long distances [1] – a topic that is of especial interest in view of the rapid growth in generation from renewables.

But the hybrid breaker does not need to await the full-scale emergence of HVDC grids to come into its own. Many present transmission proposals involve point-to-point HVDC links and hybrid breakers have a part to play here too. Besides converting power, HVDC converter stations can simultaneously contribute to the AC network's stability through reactive-power control. If the converter can be rapidly disconnected from the HVDC line in case of a fault, the converter station can go directly into stand-alone operation as a static compensation unit (STATCOM), and so continue to support the AC network's stability.

Technical demands on HVDC breakers are high. The time permitted to interrupt a current flow is shorter than for a comparable AC application due to the lower impedance of the lines (meaning the voltage drop caused by a fault can spread faster). A short-circuit fault typically has to be cleared within 5 ms in order to not affect converter stations as far away as 200 km. Because converter stations typically rely on the DC voltage being at least 80 percent of its nominal value to assure normal operation, faults must be cleared within milliseconds.

A shorter fault clearance time implies reduced requirements for power dissipation in the arrester bank, but requires a higher voltage capability of the arrester.

A purely mechanical HVDC breaker can clear a line within several tens of milliseconds, but this is too slow to fulfill the requirements of a reliable HVDC grid [2]. Nevertheless, mechanical breakers are used for such purposes as the extinguishing of fault currents. Further drawbacks of mechanical breakers are that they require additional components to generate the current zero crossing so that the current can cease to flow.

HVDC breakers based on semiconductors can easily overcome the limitations of operating speed, but because the semiconductors are permanently in the path of the current, they generate conduction losses that are typically in the range of 30 percent of the losses of the converter station.

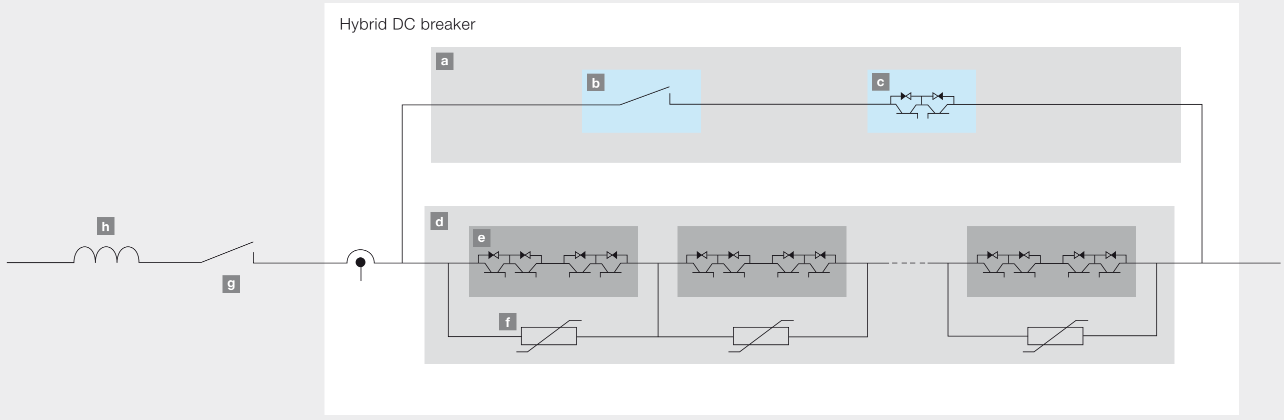
An HVDC grid is shown in → 1a. A circuit with a mechanical HVDC breaker and an arrester is shown in → 1b, and the transients that occur during breaking in → 1c. The current starts to rise when the fault occurs (the rate at which it rises is determined by the inductance of the line reactor). When the switch opens, the current is commutated to the arrester and starts to decrease. The fault current in the arrester bank establishes a counter voltage, and this reduces the fault current to zero by dissipating the energy stored both in the HVDC reactor and in the fault current path.

The total time to clear the fault consists of:
- the time during which the current rises prior to commutation
- the duration of its subsequent decrease while the line is cleared.

Both time intervals are important considerations in the design and cost of the HVDC breaker, as well as that of the line reactor.

The breaking time is governed by the response time of the protection and the action time of the HVDC switch. A longer

**2 Hybrid HVDC breaker**




a Main current branch (when current is flowing) consisting of:
b Fast mechanical disconnector HVDC breaker
c Load-commutation switch (semiconductor-based)

d Main HVDC breaker consisting of:
e Semiconductor interrupter
f Arrester bank

g Residual current breaker
h Current limiting reactor

breaking time requires the HVDC switch to have a higher maximum current breaking capability. This also increases the energy handled by the arrester and correspondingly leads to a higher cost for the HVDC breaker. It is therefore important to keep the breaking time as short as possible. When the breaking time and the maximum breaking current capability are given, the only remaining adjustable parameter is the inductance of the HVDC reactor (which governs the rate of current rise). The size of the HVDC reactor may in turn be limited by factors such as cost and the stability of the HVDC grid system.

The time allowed for fault clearance will affect the required voltage capability of the arrester as well as that of pole voltage protection. A shorter fault clearance time implies reduced requirements for power dissipation in the arrester bank, but requires a higher voltage capability of the arrester. This spells a higher pole-to-pole voltage rating, and thus adds to the costs of the HVDC breaker.

The following example provides a general impression of the relationship between the parameters mentioned. Assuming a breaking time of 2 ms, which is possible for semiconductor-based HVDC switches, and an HVDC line fault close to the HVDC switchyard, the maximum rise of the fault current will be 3.5 kA/ms for an HVDC reactor of 100 mH in a 320 kV HVDC grid with 10 percent maximum overvoltage. For a given rated line current of 2 kA, the minimum required breaking capability of the HVDC breaker is 9 kA.

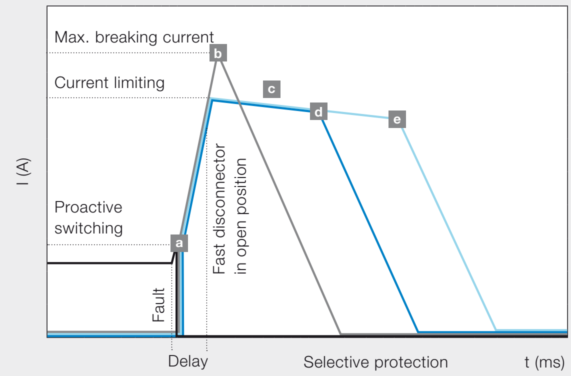
## The hybrid HVDC breaker

The hybrid HVDC breaker → 2 is based on the arrangement of → 1b but features an additional branch → 2a. This branch consists of a semiconductor-based load commutation switch → 2c connected in series with a fast mechanical disconnector → 2b.

During normal operation, the current only flows through the bypass → 2a. When an HVDC fault occurs, the load commutation switch immediately commutates the current to the main HVDC breaker → 2d. With the branch → 2a no longer carrying current, the disconnector → 2b opens, thus protecting the load commutation switch → 2c from the primary voltage that builds up across the main HVDC breaker. The required voltage rating of the load commutation switch is thus significantly reduced in comparison to a component that remains in the main current path throughout the switching cycle. Its voltage rating must only exceed the on-state voltage of the main HVDC breaker, which is typically in the kV range for a 320 kV HVDC breaker. On account of this reduced load-blocking voltage, the on-state voltage of the load commutation switch is typically in the range of several volts only. The on-state losses of the hybrid HVDC breaker are thus reduced to a percentage of the losses incurred by a pure semiconductor breaker, ie, 0.01 percent of the transmitted power.

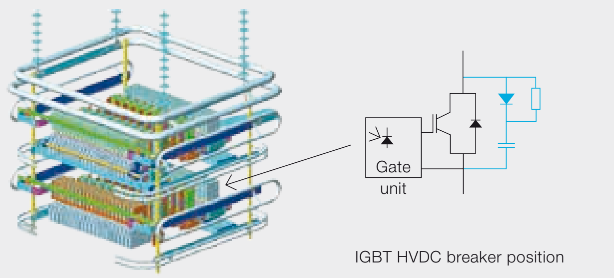
Besides converting power, HVDC converter stations can simultaneously contribute to the AC network's stability through reactive power control.

## 3 Control of hybrid HVDC breaker

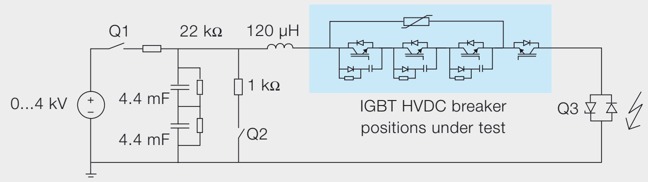



a LCS opens (LCS: load commutation switch)
b Main HVDC breaker max. current protection
c Current limiting
d External trip signal of selective protection to main HVDC breaker
e Main HVDC breaker max. temperature protection

## 4 Design of 80 kV main HVDC breaker cell




## 5 HVDC breaker component test circuit




The main semiconductor-based HVDC breaker → 2d is separated into several sections with individual arrester banks → 2f dimensioned for full voltage and current breaking capability. After fault clearance, a disconnecting circuit breaker → 2g interrupts the residual current and isolates the faulty line from the HVDC grid to protect the arrester banks from thermal overload.

The mechanical switch → 2b opens at zero current and with low voltage stress, and can thus be realized as a disconnector with a lightweight contact system. The fast disconnector will not be exposed to the maximum pole-to-pole voltage defined by the protective level of the arrester banks until after having reached the open position. Thomson drives [4] result in fast opening times and a compact disconnector design using $SF_6$ as insulating medium.

Proactive control of the hybrid HVDC breaker allows it to compensate for the time delay of the fast disconnector if the opening time of the disconnector is less than the time required for selective protection. Proactive current commutation is initiated by the hybrid HVDC breaker's built-in overcurrent protection as soon as the HVDC line current exceeds a certain overcurrent level → 3a. The main HVDC breaker delays current breaking until a trip signal is received or the faulty line current is close to the maximum breaking current capability of the main HVDC breaker → 3b.

To extend the time before the self-protection function of the main HVDC breaker trips the hybrid HVDC breaker, the main HVDC breaker may operate in current limitation mode prior to current breaking → 3c. The main HVDC breaker controls the voltage drop across the HVDC reactor to zero to prevent a further rise in the line current. The maximum duration of the current limiting mode depends on the energy dissipation capability of the arrester banks → 3d.

Fast backup protection similar to that of pure semiconductor breakers is possible for hybrid HVDC breakers in HVDC switchyards. Over-currents on the line or higher-level switchyard protection can activate the current transfer from the bypass into the main HVDC breaker or possible backup breakers prior to the trip signal of the backup protection. In case of a breaker failure, backup breakers can be activated almost instantaneously – typically within less than 0.2 ms. This avoids major disturbances in the HVDC grid, and keeps the required current-breaking capability of the backup breaker at reasonable values.

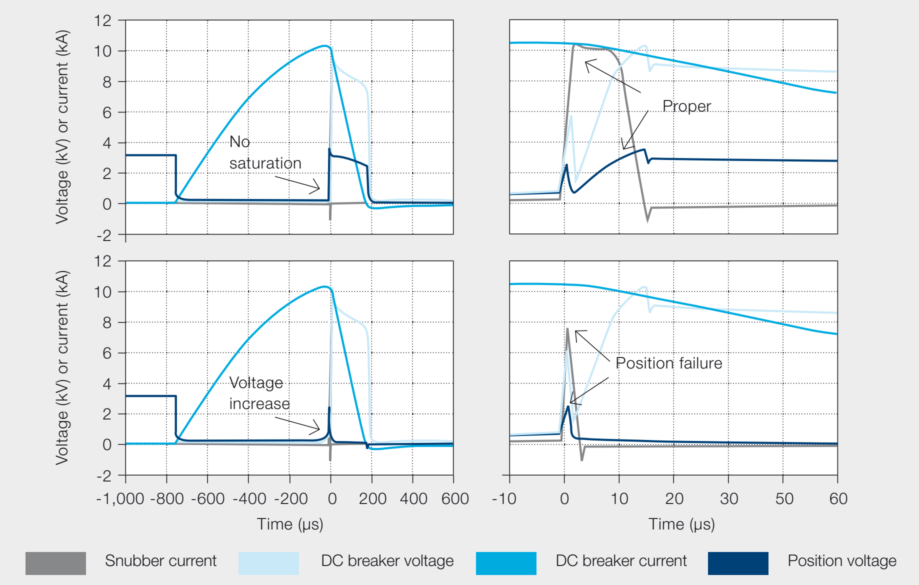
Proactive control of the hybrid HVDC breaker allows it to compensate for the time delay of the fast disconnector if the opening time of the disconnector is less than the time required for selective protection.

### Prototype design

The hybrid HVDC breaker prototype is designed to achieve a current breaking capability of 9.0 kA in an HVDC grid with a rated voltage of 320 kV and rated transmission current of 2 kA. The maximum current breaking capability is independent of the current rating, depending on the design of the main HVDC breaker only. The fast disconnector and main HVDC breaker are designed for switching voltages exceeding 1.5 p.u. in consideration of fast voltage transients during current breaking.

The main HVDC breaker → 2d consists of several HVDC breaker cells with individual arrester banks limiting the maximum voltage across each cell → 2e to a specific level during current breaking. Each HVDC breaker cell contains four HVDC breaker stacks → 4. Two stacks are required to break the current in either current direction.

6 Maximum stress tests on IGBT HVDC breaker positions (traces on the right are zoomed)




The mechanical switch opens at zero current and with low voltage stress, and can thus be realized as a disconnector with a lightweight contact system.

Each stack is composed of up to 20 series-connected IGBT HVDC breaker positions. Due to the large di/dt stress during current breaking, a mechanical design with low stray inductance was adopted. Application of press pack IGBTs with 4.5 kV voltage rating [6] enables a compact stack design and ensures a stable short circuit failure mode in case of individual component failure. Individual RCD snubbers across each IGBT module ensure equal voltage distribution during current breaking. Optically-powered gate units enable operation of the IGBT HVDC breaker independent of current and voltage conditions in the HVDC grid. A cooling system is not required for the IGBT stacks, as the main HVDC breaker cells are not exposed to the line current during normal operation.

For the design of the load commutation switch → 2c, one IGBT HVDC breaker module for each current direction is sufficient to fulfill the requirements of the voltage rating. Parallel connection of IGBT modules increases the rated current of the hybrid HVDC breaker. Series connected, redundant IGBT HVDC breaker modules improve the reliability of the load commutation switch. A matrix of 3 × 3 IGBT positions for each current direction was chosen for the present design. A cooling system is required due to the switch's continuous exposure to the line current.

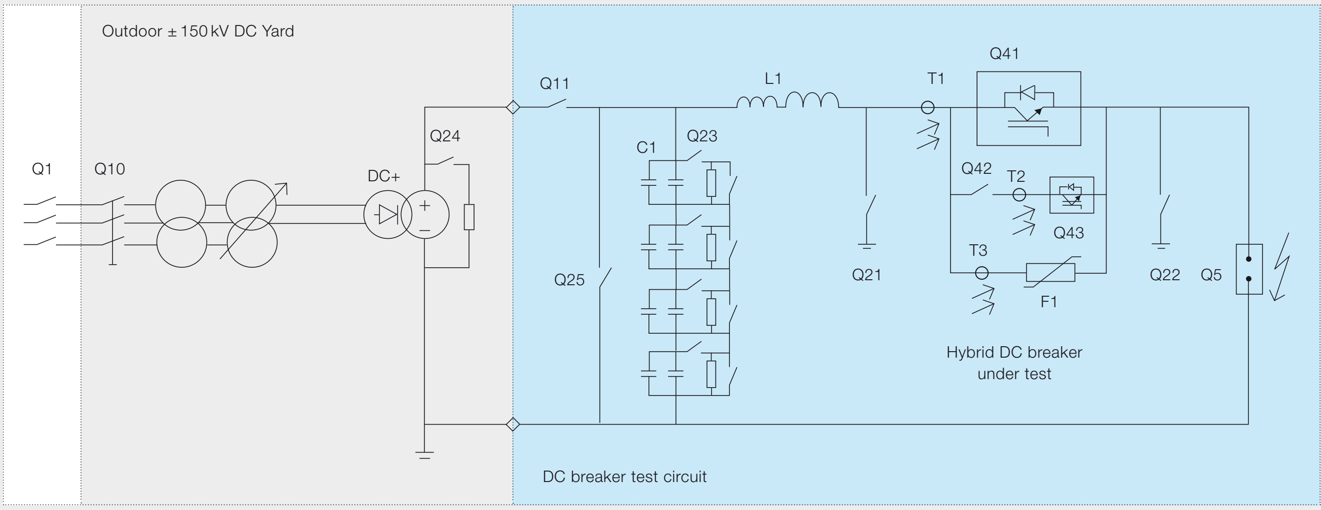
Each stack is composed of up to 20 series-connected IGBT HVDC breaker positions.

## Test results

A scaled-down prototype of the main breaker cell with three series connected IGBT modules and a common arrester bank was used to verify the current-breaking capability of 4.5 kV StakPak IGBTs [6] in the first test circuit → 5. A fourth IGBT module was connected in the opposite primary current direction to verify the functionality of the incorporated anti-parallel diode. Discharge of a capacitor bank by a thyristor switch, limited only by a minor DC reactor, represented pole-to-ground faults in the HVDC grid.

The maximum current breaking capability of the IGBT HVDC breaker cell is determined by the saturation current of the IGBT modules → 6 (rather than the safe operation area as is typical in voltage source converter applications). The series-connected HVDC breaker IGBT positions can commutate the line current into the RCD snubber circuits within 2 µs, limiting the rate of rise in voltage across the positions to 300 V/µs. Zero voltage switching reduces the instantaneous switching losses and ensures equal voltage distribution independent of the

7 ABB's containerized HVDC breaker test circuit




Successful verification testing at device and component level demonstrated the performance of the components. The complete hybrid HVDC breaker has now been verified in a demonstrator setup at ABB facilities.

tolerances in the switching characteristics of the applied IGBT modules.

The line current commutates from the RCD snubber circuit into the arrester path after the common voltage across the IGBT HVDC breaker positions reaches the protective level of the arrester bank.

The IGBT HVDC breaker positions passed the stress tests for breaking currents below 10 kA. For higher currents, the IGBT saturation current level causes an immediate voltage drop across the IGBT modules. During a purposely destructive test, the resulting internal heat dissipation within the IGBT module destroyed the encapsulated IGBT chips. Due to the use of presspack IGBTs, a reliable short circuit was created without mechanical destruction of the failed IGBT module. Since only one of the IGBT modules failed during the test, the fault could still have been cleared by the two other modules.

The nominal HVDC voltage per IGBT HVDC breaker cell is 80 kV. Due to the high voltage level, the second test setup required significantly more space. The test circuit for the hybrid HVDC breaker concept is shown in ➔ 7. The desired HVDC voltage level was built up by charging the capacitor bank C1. The reactor L1 is selected to assure the expected current derivative (di/dt) during a short-circuit fault. The short-circuit fault was initiated by the triggered spark gap Q5.

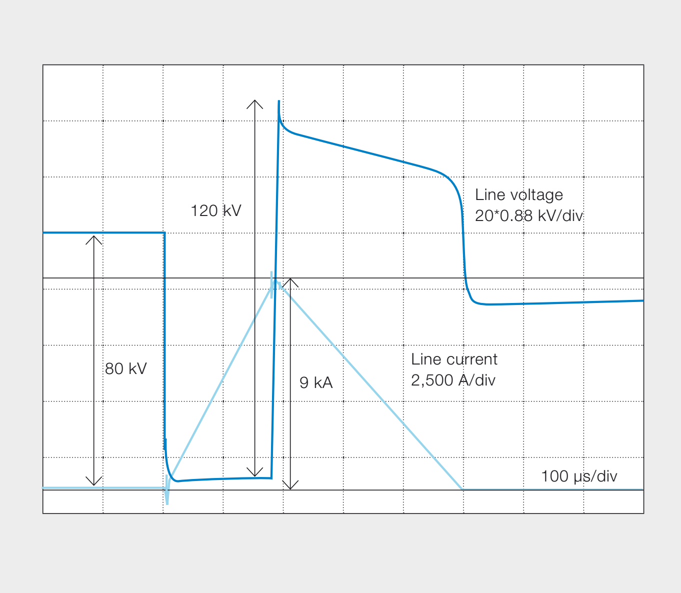
A typical test result is shown in ➔ 8. A maximum breaking current of over 9 kA is verified. The voltage across the HVDC breaker cell exceeds 120 kV during current commutation. The breaking capability of one 80 kV HVDC breaker cell thus exceeds 1 GVA. Furthermore, equal voltage distribution with a maximum voltage drop of 3.3 kV and a spread of less than 10 percent was only observed for the individual IGBT HVDC breaker positions in the HVDC breaker cell.

## Test results

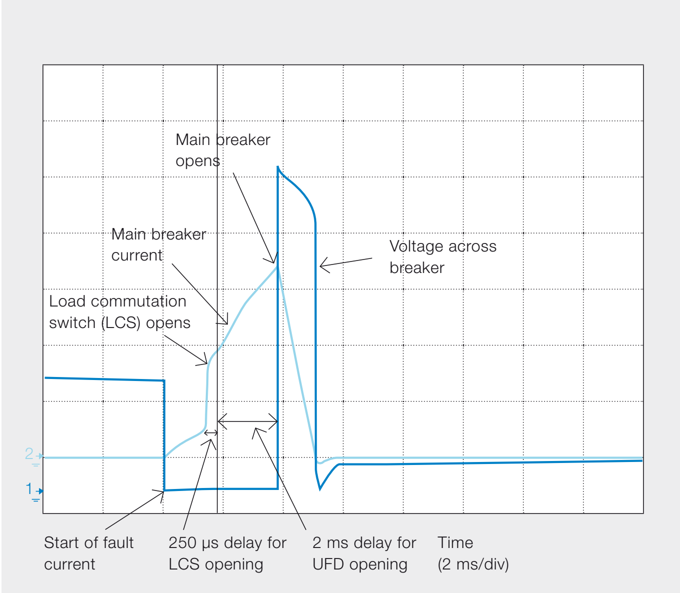
The main breaker test setup was expanded to verify the complete hybrid HVDC breaker concept. A second capacitor bank and large reactors were installed to limit the rate of line current rise to typical HVDC grid values. The ultra-fast disconnector and load commutation switch are included in the system configuration.

Introduction of bimode insulated gate transistor (BIGT) technologies will double the current breaking capability of presspack modules.

8 Verification of modular IGBT HVDC breaker cell




9 Verification of the hybrid HVDC breaker system




The next step is to test such a breaker in a real HVDC transmission line.

Successful verification testing at device and component level demonstrated the performance of the components. The complete hybrid HVDC breaker has now been verified in a demonstrator setup at ABB facilities. A breaking event with a peak current of 9 kA and 2 ms delay time for opening the ultra-fast disconnector in the branch parallel to the main breaker is shown in → 9. The maximum rated fault current of 9 kA is the limit for the existing generation of semiconductors. The next generation of semiconductor devices will allow breaking performance of up to 16 kA. The purpose of the tests was to verify switching performance of the power-electronic parts, and the opening speed of the mechanical ultra-fast disconnector. The assembly under test consisted of one 80 kV unidirectional main breaker cell, along with the ultra-fast disconnector and load commutation switch. The higher voltage rating is accomplished by connecting several main breaker cells in series. Tests have not only been carried out for normal breaking events, but also for situations with failed components in the breaker.

## Outlook

Introduction of bimode insulated gate transistor (BIGT) technologies [7] incorporating the functionality of the reverse conducting diode on the IGBT chips will double the current breaking capability of existing presspack modules (see also "The two-in-one chip" on pages 19–23 of this edition of *ABB Review*).

Fast, reliable and nearly zero-loss HVDC breakers and current limiters based on the hybrid HVDC breaker concept have been verified at component and system levels for HVDC voltages up to 320 kV and rated currents of 2 kA, removing a major obstacle in the realization of HVDC grids. The next step is to test such a breaker in a real HVDC transmission line.

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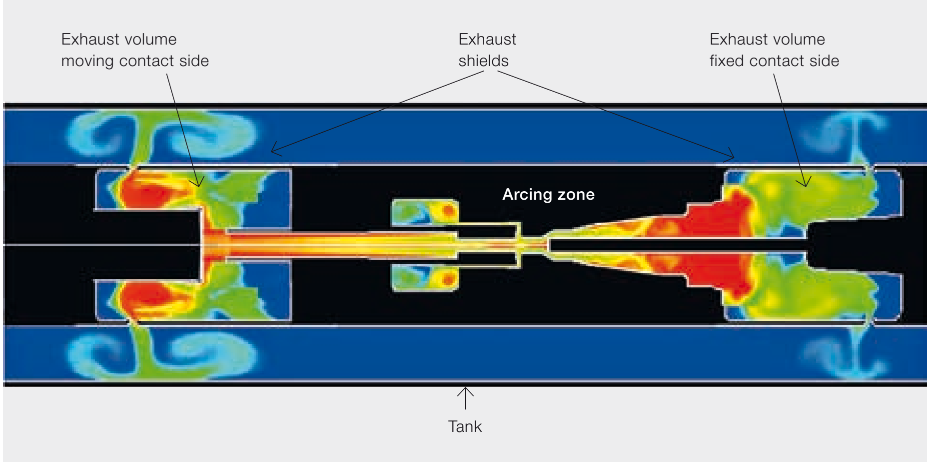
# Breaking new ground

## A circuit breaker with the capacity to switch 15 large power plants

HELMUT HEIERMEIER, RETO KARRER – The power networks that span the landscape and bring electrical energy to cities and towns are constantly evolving. In particular, operating voltages are being increased, mostly to minimize transportation losses. This places higher demands on the critical elements that control and protect these networks – the circuit breakers. At the heart of the circuit breaker lies the interrupter – the chamber where the switching physically takes place. The changing technical and market conditions, as well as new international standards, have brought about the need to develop a new generation of interrupter.

1 Example of a computational fluid dynamics simulation of a metal-enclosed circuit breaker




The networks that keep crucial electrical power flowing to society are being run at ever-higher voltages to minimize transportation losses and reduce environmental impact. This higher voltage, and other demands, means that a key element for the protection and control of power networks, the circuit breaker, also has to evolve. Of critical importance is the availability of the circuit breaker, as this directly impacts the reliability of the electrical network itself.

Reduced breaker component count and low operating energy lead to lower risk of unexpected outages. Additionally, if the size of the breaker can be reduced, cost and space requirements will also fall.

With this in mind, ABB began development of a new, single-chamber breaker for 420 kV networks. This new interrupter should fulfill the latest IEC and ANSI/IEEE international standards as well as known special requirements from different markets worldwide. Since both the nominal and the short-circuit currents that are to be handled are expected to increase in the future, a rated nominal current of 5 kA and a rated short-circuit current of 63 kA based on 50 Hz and 60 Hz were targeted.

Additional requirements were:
- Small bay size (it should be possible to put a complete bay into a standard container)
- Full-short line fault switching capability without needing a line-to-ground capacitor
- Reduction in $SF_6$ gas volume
- Lowest possible reaction forces (impact on buildings and foundations)
- Small, standard drive
- Two-cycle interrupt time

## Circuit breakers

A circuit breaker is a remarkable piece of equipment. It has to cope with a range of currents from 1 A up to several tens of kA; it has to withstand a large range of voltage scenarios, eg, very fast voltage rises and long-term AC stresses; it must perform mundane daily switching operations as well as emergency interruption of short-circuit currents; it may be inactive for a long period but must then be capable of emergency interruption of faults within a few milliseconds.

## Designing a new breaker

Many very different factors need to be considered when designing a new switching device and deciding on a new technology.

### Capacitive switching capability

This duty is characterized by relatively small currents but high voltages across circuit breaker contacts, so a high dynamic voltage withstand capability is required. The voltage withstand capability needs to be greater than the rising network voltage during the opening operation of the circuit breaker. This is best characterized as a race between the opening contacts and the transient voltage buildup. It is vital that the breaker wins this race since no voltage breakdowns can occur as these can lead to a voltage escalation that stresses substation components and overhead lines. In other words, this new breaker has to have a high contact speed so that a high dielectric withstand capability is reached in a very short time.

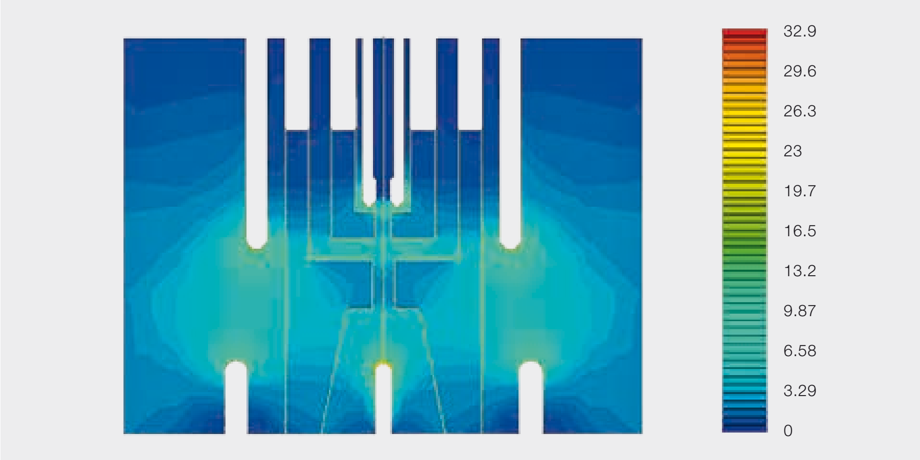
Reduced breaker component count and low operating energy lead to the lowest risk of unexpected outages. Additionally, smaller breakers reduce cost and real-estate requirements.

**Title picture**

Power lines at ever-higher voltages are driving new developments in high-voltage technology. How do the latest circuit breakers deal with the new challenges?

A single-chamber breaker for 420 kV networks with 5 kA rated nominal current, a rated short-circuit current of 63 kA at 60 Hz and no line-to-ground capacitor requirement was targeted.

2 Example of an electric field simulation of the arcing zone




In international standards, this aspect is covered by a very detailed test procedure and an extensive test program.

**Full-short line fault interrupting capability**

This requires a high gas pressure in the volume between the breaker contacts in order to provide enough cooling power to quench the arc so interruption will be successful. This pressure buildup is one key value for fast fault-clearing capability. A single-chamber interrupter designed for high short-circuit interrupting capability requires a high clearing pressure.

New materials and production techniques were evaluated to help identify a product with costs comparable to conventional offerings.

**Terminal fault interrupting capability**

Since one of the requirements is to stay within a two-cycle interrupting time, a short opening time is required, which leads to higher asymmetrical requirements than for earlier breakers. Interrupting at high asymmetry levels leads to high-pressure buildups that must be handled by the drive as well as the exhaust and nozzle system. For this new breaker, this means that high energy inputs into the arcing zone as well as the exhaust system need to be safely handled.

**Transformer-limited fault requirements**

This special requirement, which has to be met at some locations, comes up when a fraction (7 to 30 percent) of the rated short-circuit current is present together with a very high rate of rise of the recovery voltage (the voltage that appears across the terminals after current interruption.) In order to withstand such severe stress, it is necessary to build up a high dynamic voltage withstand capability very quickly after current interruption. This means the hot gas between the arcing contacts needs to be replaced by cold gas as swiftly as possible.

## Deciding on a switching technology

Circuit breakers currently come in several varieties, all of which have their own merits:

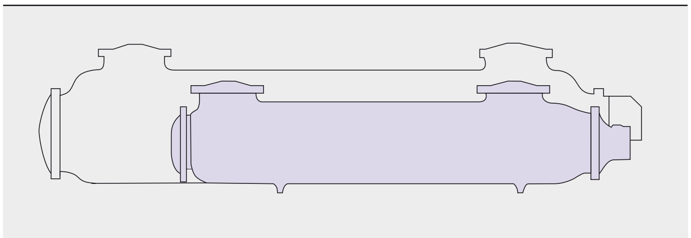
- Puffer breakers
- Advanced puffer breakers
- Puffer-assisted self-blast breakers
- Pure self-blast breakers
- Self-blast breakers with linear double moving system
- Self-blast breakers with nonlinear double moving system

The virtues of several of these concepts were combined when developing the new breaker, which has been designated as an advanced puffer breaker with a nonlinear double moving system. Such an approach has advantages:

- High and adjustable contact speed.
- Low moving masses, leading to low reaction forces.

3 Full laboratory evaluation of test designs were carried out.

4 The volume of the circuit breaker was significantly reduced.



5 First installation in Switzerland: old (right) versus new (left).

- Fast opening times (using a standard, low-energy hydraulic spring mechanism.)
- Low ratio between no-load pressure buildup and maximum pressure buildup (leading to low temperatures of the extinguishing gas during power interruption.)
- Low mechanical stress on moving parts due to reduced speed of certain parts.
- Even for higher asymmetry levels, maximum pressure buildup does not overstress the arcing unit parts

Reaction forces are lower than any other solution, so physical infrastructure will be less expensive.

mechanically since it is possible to limit the maximum pressure generated.

The development relied heavily on simulation software to mimic different physical effects, like flow, pressure buildup and electric fields, during current interruption → 1 – 2. Finite element method (FEM) tools assisted mechanical analysis. Test objects were equipped with various measurement sensors to obtain data with which to improve and crosscheck the simulation tools. Furthermore, tests have been carried out to determine the limits of the test device. In parallel to the development, new materials and advanced production techniques were evaluated to help identify a product with costs comparable to conventional offerings → 3.

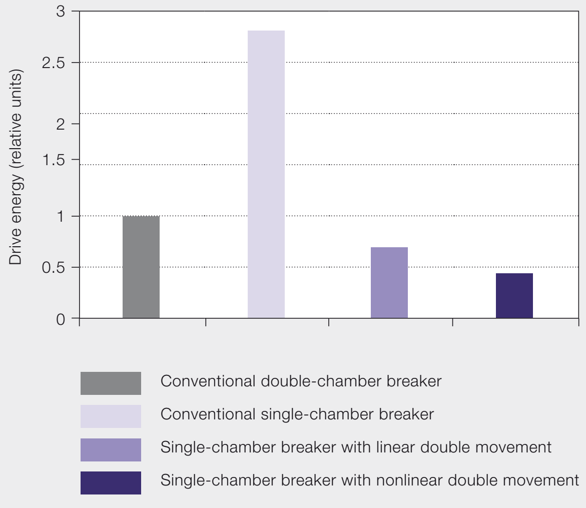
### Project results

The development achieved or surpassed targets when compared with the previous breaker generation:

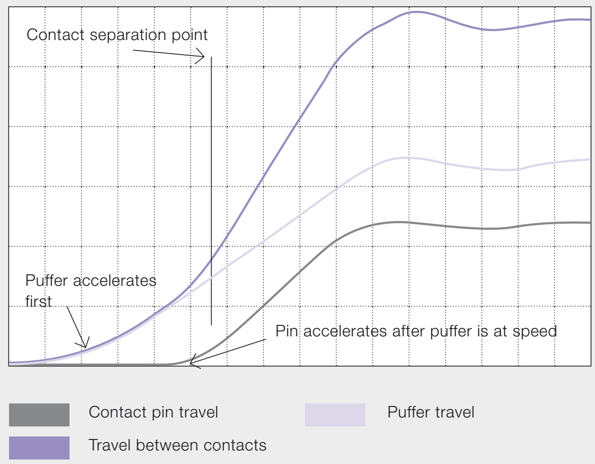
- 50 percent drive energy reduction.
- 30 percent $SF_6$ volume reduction → 4.
- 50 percent gas-insulated switchgear (GIS) bay size volume reduction (301 ELK 3-2, 147 ELK 3-1) → 5.
  Further bay size reduction will be achieved with adapted GIS parts. This improved bay will fit into a standard container for transportation as well as

50 percent drive energy reduction, 50 percent bay size volume and 30 percent $SF_6$ volume reduction were achieved.

6 A comparison of the drive energy needed (relative units)




7 The switching scheme (axes in relative units). The switching characteristics are in line with newest IEC and IEEE standards.




The development relied heavily on simulation software to mimic different physical effects, like flow, pressure buildup and electric fields, during current interruption. FEM tools assisted mechanical analysis.

for emergency use as a container switchyard (as shown at the 2012 Hanover Fair.)

A conventional two-chamber solution uses twice the drive energy of the new nonlinear double movement system (a single chamber, with one side driven, nearly five times) ➔ 6. The moving mass per chamber is about the same (single or double chamber) though there is a slight increase of moving mass for the double movement system (pin and levers).

The reaction forces are lower than any other solution, so physical infrastructure will be less expensive. In addition, the acceleration of the moving mass can be staggered and the pin movement can be reduced, further reducing energy requirements ➔ 7.

The new breaker, which can be used in dead tank breaker and Plug and Switch System (PASS) applications as well as GIS, met all the major targets that were set. This new product is a modern, competitive breaker that fulfills the newest international standards. In terms of sheer capability, it is interesting to note that the short-circuit power that a single chamber is able to switch is nearly 23 GW, corresponding to the nominal power of approximately 15 nuclear power stations.

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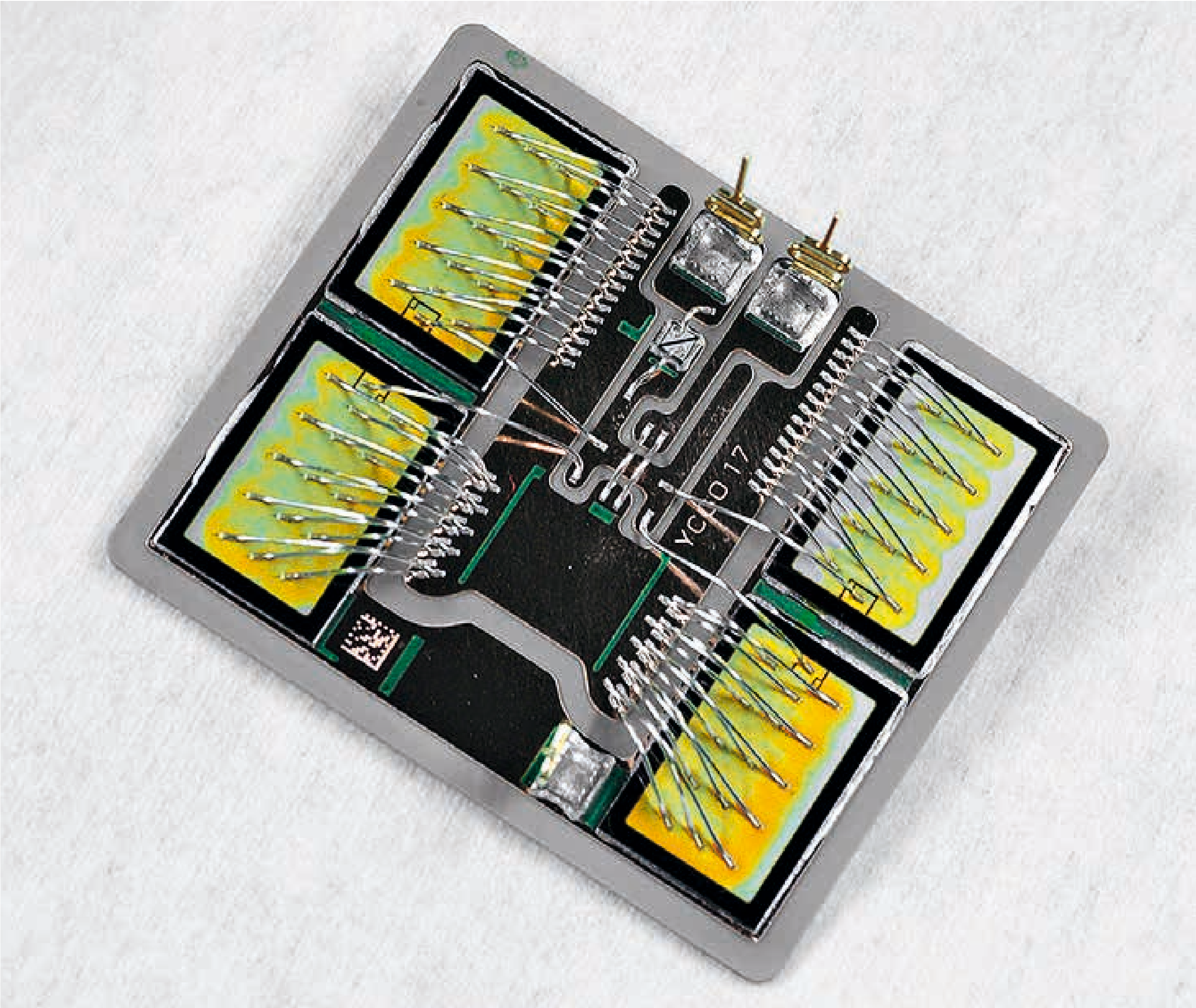
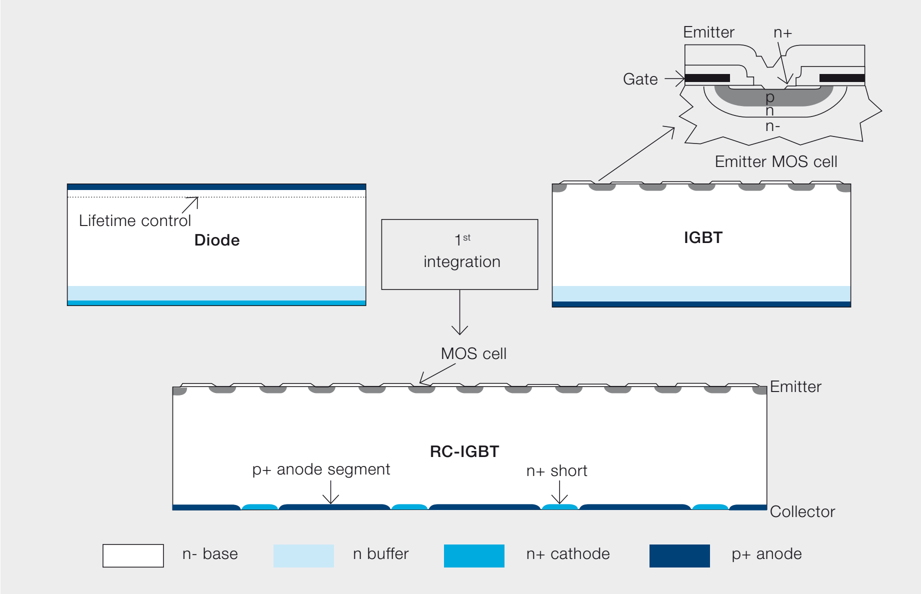


# The two-in-one chip

## The bimode insulated-gate transistor (BIGT)

MUNAF RAHIMO, LIUTAURAS STORASTA, CHIARA CORVASCE, ARNOST KOPTA – Power semiconductor devices employed in voltage source converter (VSC) applications typically carry current in one direction only. VSC circuit topologies with inductive loads, however, commonly pair switchable elements that conduct in one direction with (freewheeling) diodes that conduct in the other (reverse direction or anti-parallel). It has thus long been a goal of semiconductor manufacturing to achieve full integration of the two into a single device, and ideally, into a single silicon structure. Such integration opens the road to higher power densities and more compact systems while at the same time simplifying manufacture. In IGBT[1] technology, reverse-conducting switches integrated onto a single chip have typically been restricted to lower-power devices and special applications. ABB has achieved a breakthrough with its BIGT (bimode insulated-gate transistor), integrating a freewheeling diode into the switching device while achieving operating characteristics previously restricted to far larger devices.

1 First integration step: reverse conducting IGBT (RC-IGBT)




Due to the inherent technical challenges associated with the concept of integrating switching devices with anti-parallel diodes, such an approach has (in recent years) only been employed for lower power components such as IGBTs and MOSFETs[2] and for special applications. Furthermore, for large-area bipolar devices, such as the IGCT[3], monolithic integration has been utilized but with the IGCT and diode utilizing fully separated silicon regions.

Development efforts at ABB have over the past few years targeted a fully integrated high-power IGBT and diode structure on a single chip. The main target application was for hard-switching mainstream inverters[4]. The new power semiconductor device concept is referred to as the bimode insulated gate transistor (BIGT). The first prototype devices, with voltage ratings above 3,300 V demonstrated higher power densities than conventional chips, and improved over-all performance. The BIGT was designed in accordance with the latest IGBT design concepts while fully incorporating an optimised integrated anti-parallel diode in the same structure. In addition to the power and size impact of the BIGT, the device also provides improved turn-off softness in both operational modes, high operating temperature capability, higher fault condition performance under IGBT short circuit and diode surge current[5], and improved current sharing when devices are operating in parallel. In addition, by utilizing the same available silicon volume in both IGBT and diode modes, the device provides enhanced thermal utilization due to the absence of device inactive operational periods and hence, improved reliability.

The practical realization of the single chip BIGT technology will provide a potential solution for future high voltage applications, demanding compact systems with higher power levels, especially those with high diode current requirements which could prove to be beyond the capability of the standard two-chip approach.

Several existing and new technologies were employed for the BIGT in order to realize the integration of the IGBT and diode functionalities.

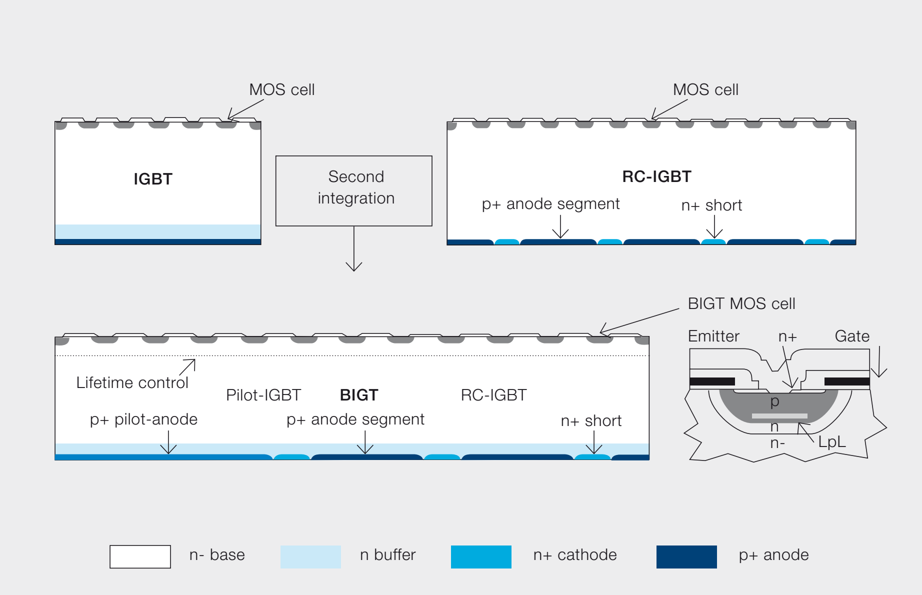
## The integration challenge

In modern applications employing IGBT modules, the diode presents a major restriction with regard to its losses, performance and surge-current capability. Both limits are a result of the historically limited area available for the diode: a typical IGBT to diode area ratio is in the region of 2:1. These limits were essentially established after the introduction of modern low-loss IGBT designs. The approach of increasing the diode area is not a preferred solution, and in any case remains constrained by the footprint of the package designs. The demand for increased power densities of IGBT and diode components has thus shifted the focus to a solution integrating IGBT and diode, or what has normally been referred to as the reverse-conducting IGBT (RC-IGBT).

Until recently, the use of RC-IGBTs has been limited to voltage classes below 1,200 V for specialised soft switching applications with reduced diode requirements. Conventionally, the realization of such a device for high voltage and mainstream hard switching applications has always been hindered by design and process issues, resulting in a number of performance drawbacks and trade-offs summarized as follows:

**Title picture**
ABB's new BIGT integrates reverse-conducting diode functionaility into the structure of the semiconductor switch.

2 Second integration step: the bimode insulated gate transistor (BIGT)




– Snap-back[6] in the IGBT on-state I–V characteristics – the MOSFET shorting effect
– Trade-off of IGBT on-state versus diode reverse-recovery losses – the plasma shaping effect
– IGBT versus diode softness trade-off – the silicon design effect
– Safe operating area (SOA) – the charge uniformity effect

In the past few years, development efforts at ABB aimed at tackling the above issues have resulted in an advanced RC-IGBT concept, the BIGT.

## The BIGT concept

The BIGT concept is based on two integration steps. The first of these is illustrated in ➔ 1. The IGBT and diode share a single structure. On the collector side, alternating n+ doped areas are introduced into an IGBT p+ anode layer. These then act as a cathode contact for the internal diode mode of operation. The area ratio between the IGBT anode (p+ regions) and the diode cathode (n+ regions) determines which part of the collector area is available in IGBT or diode modes respectively. During conduction in diode mode, the p+ regions are inactive and do not directly influence the diode conduction performance. However on the other hand, the n+ regions act as anode shorts in the IGBT mode of operation, strongly influencing IGBT conduction mode.

One of the implications of anode shorting is the voltage snapback referred to previously. This is observed as a region of negative resistance in the device's IGBT mode I–V characteristic. This effect will have a negative impact when devices are connected in parallel, especially at low temperature conditions. To resolve this issue, a second integration step was required. It has been shown that the initial snap-back can be controlled and eliminated by introducing wide p+ regions into the device, also referred to as a pilot-IGBT. This approach resulted in the BIGT concept which, in principle, is a hybrid structure consisting of an RC-IGBT and a standard IGBT in a single chip ➔ 2.

The pilot area is centralized on the chip to obtain better thermal distribution and reduced current non-uniformities. It is also designed to provide the outermost functional reach within the chip while ensuring a large RC-IGBT region. Alternating p+ and n+ regions are arranged in a striped structure with an optimized radial layout to ensure smooth and fast transition in the IGBT conduction mode from the pilot area to rest of the chip ➔ 3.

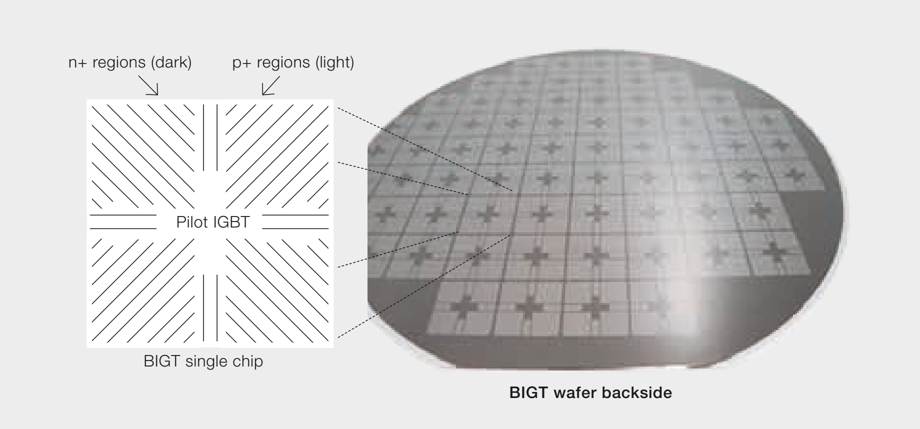
Several existing and new technologies were employed for the BIGT in order to realize the integration of the IGBT and diode functionalities. First, it is important to note that technology platforms already in use by ABB, such as the high voltage soft-punch-through (SPT) buffer and enhanced-planar cell concepts[7] have been

Development efforts over the past few years at ABB have targeted a fully integrated high power IGBT and diode structure on a single chip.

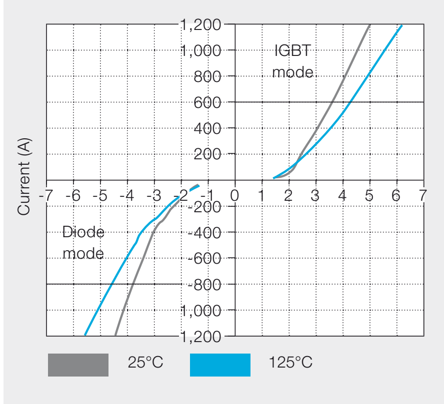
**Footnotes**

1 An IGBT (insulated-gate bipolar transistor) is a voltage-controlled semiconductor switch seeing widespread use in power electronics.
2 A MOSFET (metal-oxide-semiconductor field-effect transistor) is a semiconductor device used in both switching and amplification applications. It's switching applications are typically of lower power than IGBTs.
3 An IGCT (integrated gate-commutated thyristor) is a GTO (gate turn-off thyristor) optimized for hard switching and using a gate-drive integrated into the device. For more background on different semiconductor technologies, see "From mercury arc to hybrid breaker" on pages 70–78 of this edition of *ABB Review*.
4 Hard switching is a current turn-on / turn-off involving high dv/dt and di/dt during the switching.
5 Surge-current capability is a device's ability to accept a sudden and short current peak (far the device's its nominal current rating) without suffering damage.
6 Snap-back is an effect observed in IGBTs in which the on-state voltage can display a brief peak during turn-on, also shown in figure 9.
7 See "Switching to higher performance", pages 19–24, *ABB Review* 3/2008.

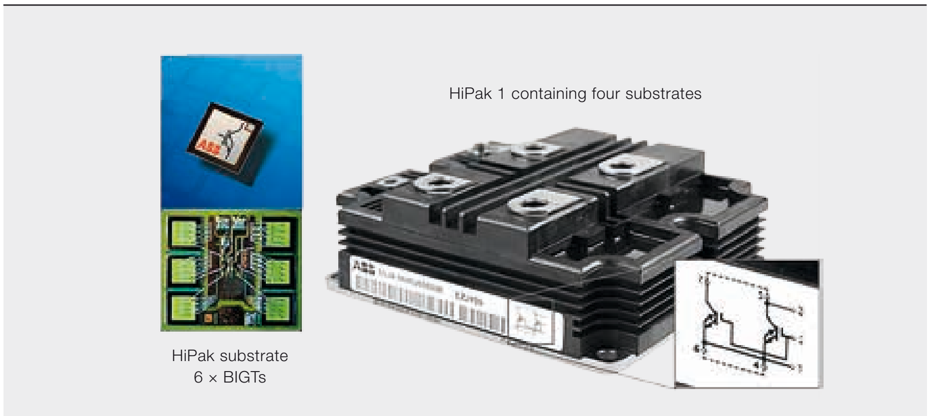
**3 The BIGT backside design**



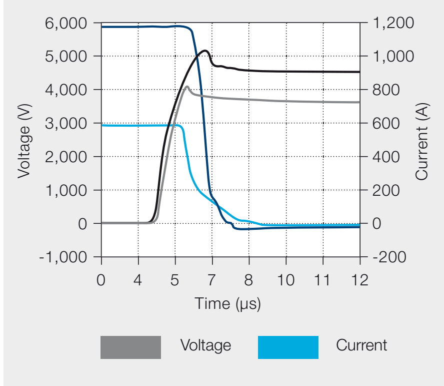

**5 6.5 kV/600 A BIGT HiPak 1 on-state characteristics**




**4 The 6.5 kV/600A BIGT HiPak 1**




**6 6.5 kV/600 A BIGT HiPak 1 IGBT mode turn-off waveforms**





The BIGT technology is initially being developed for high voltage devices and has been demonstrated at module level with voltage ratings ranging from 3.3 kV and up to 6.5 kV.

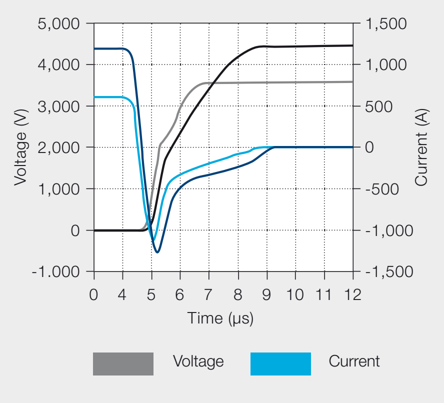

main enablers of this integration. In addition to their well known robustness and low loss properties, the SPT optimum doping profile contributes significantly to reducing the snap-back effect while the miniaturized enhanced-planar stripe cell design plays an important role in reducing the diode conduction and switching losses without having a negative impact on IGBT performance. Furthermore, in addition to a standard axial lifetime control, a precise local p-well lifetime (LPL) process was also devised (as shown in ➔ 2) to improve the trade-off of IGBT on-state versus diode reverse recovery losses. Finally, due to the anode shorts design, the BIGT has inherited a number of properties that have resulted in device performance advantages in both operation modes such as soft switching behavior under extreme conditions and very low leakage currents for operating at higher maximum junction temperatures.

## BIGT performance

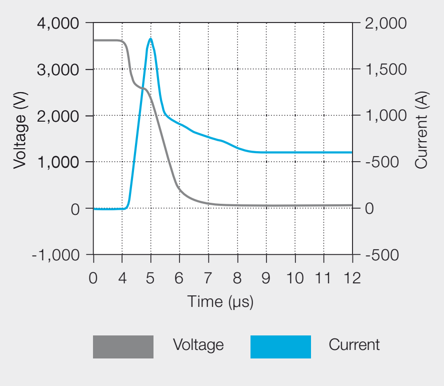
The BIGT technology is initially being developed for high voltage devices and has been demonstrated at module level with voltage ratings ranging from 3.3 kV and up to 6.5 kV. The test results presented here were carried out on the recently created 6.5 kV standard footprint HiPak 1 modules (140 × 130) with a current rating of 600 A ➔ 4.

A conventional IGBT/diode substrate will normally be occupied by four IGBTs and two diodes while the new substrate is now capable employing six BIGT chips all operating all in IGBT or diode mode. The BIGT advantage is clearly demonstrated her with the HiPak 1 module containing four BIGT substrates for a total of 24 BIGT chips being practically able to replace the larger HiPak 2 IGBT module (140 × 190) which normally contains six substrates having a total of 24 IGBTs and 12 diodes. The larger standard IGBT module has the further disadvantage of employing a much smaller diode area. This area is normally a limiting factor when in rectifier mode of operation and for the surge current capability. On the other hand, a larger HiPak 2 BIGT module is feasible with a total of 36 BIGT chips and its rating can potentially reach up to 900 A.

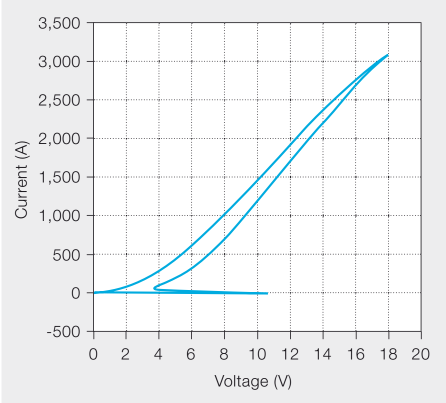
**7 6.5 kV/600 A BIGT HiPak 1 diode mode reverse-recovery waveforms**



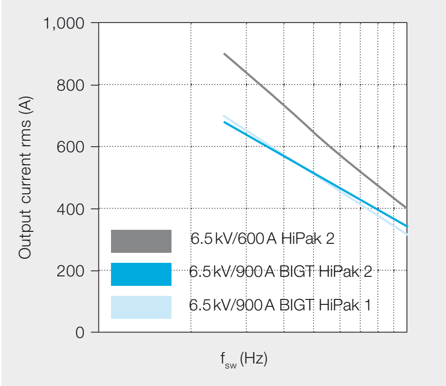

**8 6.5 kV/600 A BIGT HiPak 1 IGBT mode turn-on waveforms**




**9 6.5 kV BIGT substrate diode mode surge-current capability**




**10 Output current capability of the 6.5 kV HiPak 1 and HiPak 2 modules in inverter modes**




The BIGT HiPak 1 modules were tested under static and dynamic conditions, similar to those applied to state-of-the-art IGBT modules. The on-state characteristics of the BIGT in IGBT and diode modes are shown in ➔ 5. An on-state of approximately 4.2 V at 125 °C is shown at the 600 A nominal current for both operational modes. In addition, supporting the safe parallel connection of chips, the curves show a strong positive temperature coefficient even at very low currents and in both modes of operation. This is due to the optimum emitter injection efficiency and lifetime control employed in the BIGT structure.

For dynamic measurements at nominal conditions, the DC-link voltage was set to 3,600 V, while for SOA characterization it was increased to 4,500 V. All measurements were performed at 125 °C with a fixed gate resistor of 2.2 Ω, a gate emitter capacitance of 220 nF and a stray inductance of 300 nH. In ➔ 6 – 7, the module-level IGBT and diode turn-off waveforms are presented respectively under nominal and SOA conditions. BIGT turn-off waveforms have always displayed smoother performance than standard IGBT/diode modules. The BIGT did not show oscillations or snappy characteristics under any conditions. ➔ 8 also shows the BIGT turn-on behaviour under nominal conditions. The total IGBT and diode switching losses for the tested module were in the range of 10 Joules which is similar to that measured for the current standard 6.5 kV/600 A HiPak 2 IGBT module.

## A HiPak 2 BIGT module is feasible with a total of 36 BIGT chips and its rating can potentially reach up to 900 A.

➔ 9 shows the last pass measurement of the BIGT diode mode surge current capability for one substrate (rated 150 A), reaching up to 3,000 A. It is clear that the BIGT HiPak 1 offers the uncompromised surge performance of a corresponding HiPak 2 IGBT/diode module, and the BIGT HiPak 2 module goes well beyond that. Finally, standard reliability verifications and frequency operation tests were carried out successfully on BIGT modules and chips.

Based on these results, The BIGT device is expected to outperform a present state-of-the-art IGBT and diode in both soft and hard switching conditions, and also fulfil the rigorous robustness standards required of power devices today. ➔ 10 shows the simulated output current performance in inverter mode for the 6.5 kV BIGT HiPak1 and HiPak 2 modules compared to today's HiPak 2 IGBT module at 125 °C. The BIGT rectifier mode output current simulations will provide even higher capability due to the large diode area available in the BIGT module. The BIGT technology will pave the way for future generations of system designs for providing higher power densities and exceptional overall performance without any limitations coming from diode performance.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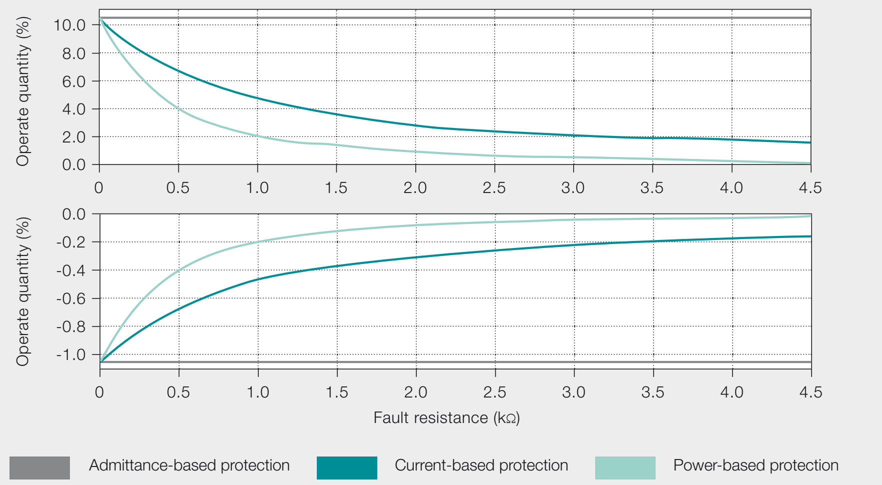
# Easy admittance

## The ultimate earth-fault protection function for compensated networks

ARI WAHLROOS, JANNE ALTONEN, PRZEMYSLAW BALCEREK, MAREK FULCZYK – A compensated network is a network in which the system neutral point is grounded through a compensation coil. Such grounding reduces capacitive earth-fault currents produced by the network to close to zero at the fault point and alleviates the conditions for self-extinguishment of earth faults without the need to trip breakers and cause customer outages. This is why increasing numbers of medium-voltage networks are being changed to the compensated type. However, the low fault currents in compensated networks challenge traditional earth-fault protection principles. An alternative principle, based on measured neutral admittance, was developed in the early 1980s in Poland. This simple, but very smart, principle has many advantages over traditional methods and it can be applied to all types of unearthed and compensated networks, including feeders with distributed compensation. Neutral-admittance-based earth-fault protection functionality is now available in ABB's Relion® products REF615 and REF630.

1 Different earth-fault protection principles showing magnitude of the operate quantity as a percentage of nominal value of $Y_o$, $I_o$ or $S_o$ versus fault resistance




In the early 20th century, Waldemar Petersen discovered that by connecting an inductance to the neutral point of the main transformer, the capacitive earth-fault current produced by the network could be reduced to close to zero and, thus, the majority of arcing earth faults would self-extinguish. Today, these inductance elements are called Petersen coils, compensation coils or arc suppression coils.

Temporary earth faults cause the majority of outages and using compensation coils can significantly reduce outage frequency, resulting in a more reliable and higher quality supply. Compensation also allows continuation of network operation during a sustained earth fault, assuming the conditions for hazardous voltages set by legislation and regulations are met.

For these reasons, the application of compensation coils has recently become popular in medium-voltage (MV) distribution networks worldwide.

## Protection schemes challenged in compensated networks

Although compensation delivers operational benefits, earth-fault protection of the network becomes more complicated due to the extremely low fault currents resulting from the compensation effect of the Petersen coil. Often, these currents are only a fraction of the normal load current, too low to trip conventional overcurrent relays.

Traditionally, earth-fault protection in compensated networks has been based on the active component of the residual current (eg, the Iocosphi principle) or that of the residual power (the Wattmetric principle). An alternative principle, based on measured neutral admittance, was formulated in the early 1980s in Poland, where it has become a functional requirement for local utilities.

> Temporary earth faults cause the majority of outages. Using compensation coils can significantly reduce these, resulting in a more reliable and higher quality supply.

## Neutral admittance protection – concept

Neutral admittance protection, like other earth-fault protection schemes, is based on the fundamental frequency components of residual current ($\underline{I}_0$) and residual voltage ($\underline{U}_0$). But, instead of residual current or power ($\underline{S}_0 = \underline{U}_0 \cdot \underline{I}_0$) being the operate quantity, the protection is based on monitoring the value of the measured neutral admittance, $\underline{Y}_0$, defined as the quotient of residual current and residual voltage phasors:

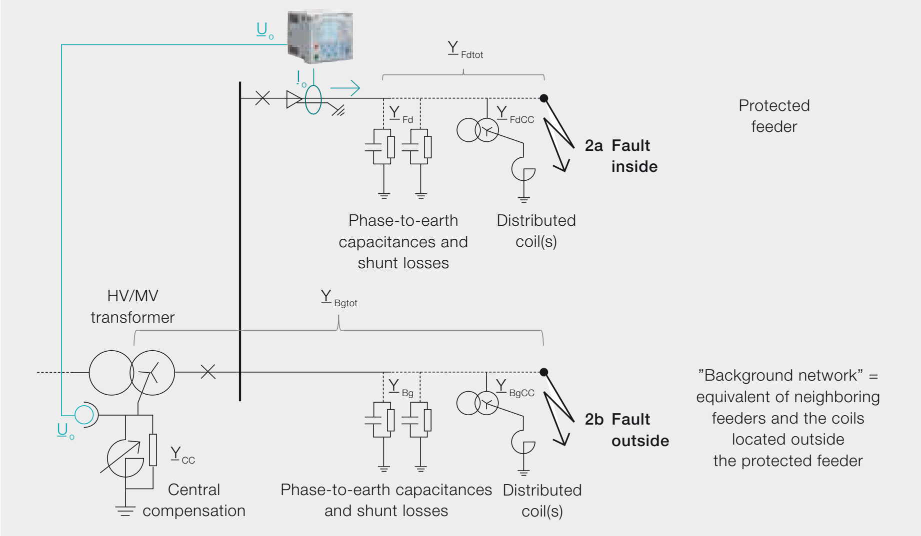
$$\underline{Y}_0 = \frac{\underline{I}_0}{\underline{U}_0} = G + j \cdot B,$$

where G is the conductance and B the susceptance. The measured admittance is directly related to known system parameters, ie, the shunt resistances, capacitances and inductances of the network. The resistive part of neutral admittance, ie, the conductance, G, corresponds to the shunt resistances and losses of the system and the imaginary part, ie, the susceptance, B, corresponds to the shunt capacitances and shunt inductances of the system. As these values are the base for earth-fault protection analysis of the network, their values are always available and are typically stored in the distribution management systems (DMSs).

The main advantage of monitoring the ratio of $\underline{I}_0$ and $\underline{U}_0$, ie, the neutral admittance, is that, ideally, this ratio remains constant with changing fault resistance as both $\underline{I}_0$ and $\underline{U}_0$ decrease with increasing fault resistance [1]. This is in contrast

**Title picture**
Compensated networks improve reliability of supply, but make it tough to implement earth-fault protection. How does a method invented in Poland in the 1980s save the day?

2 Simplified single-phase equivalent circuit of a compensated network with an earth fault located either in the protected feeder (2a) or in the background network (2b)




to traditional earth-fault protection, where the magnitude of the operate quantity, based on residual current or power, is greatly decreased by the fault resistance. This feature of the neutral admittance principle improves the sensitivity of the earth-fault protection and enhances discrimination between fault and nonfault conditions, especially at higher fault resistance values → 1.

The main advantage of monitoring the ratio of Io and Uo, ie, the admittance, is that, ideally, the result is not affected by fault resistance in the fault spot.

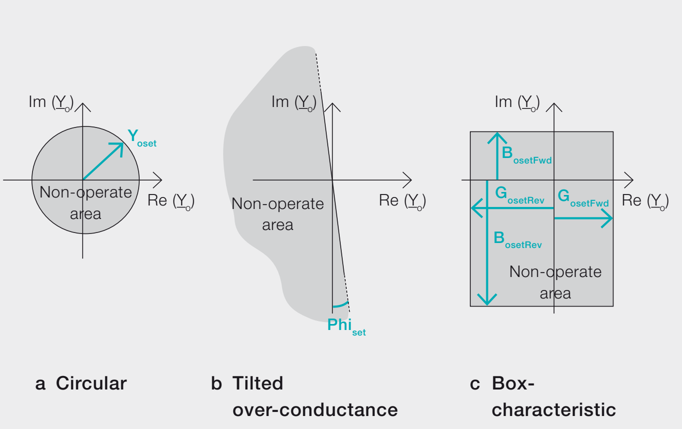
## Admittance protection theory in a nutshell

In the case of a fault outside the protected feeder, the measured admittance equals the negative of the total neutral admittance of the protected feeder, $-\underline{Y}_{Fdtot}$. This admittance is the sum of the total admittances of the phase conductors of the protected feeder, $\underline{Y}_{Fd}$, and the admittances of the compensation coils located in the protected feeder, $\underline{Y}_{FdCC}$ (if applicable). The resistive part of the measured admittance corresponds to the resistive shunt losses of the feeder and the losses of the distributed coils located in the protected feeder. The imaginary part is proportional to the sum of phase-to-earth capacitances of the feeder and the inductances of the distributed compensation coils located in the protected feeder → 2.

In the case of a fault inside the protected feeder, when the protection must operate, the measured admittance equals the total neutral admittance of the background network, $\underline{Y}_{Bgtot}$. This admittance is the sum of the total admittances of the phase conductors of all the other feeders of the substation, $\underline{Y}_{Bg}$, and the admittances of the compensation coils located outside the protected feeder in the substation, $\underline{Y}_{CC}$, or in the neighboring feeders, $\underline{Y}_{BgCC}$. The real part of the measured admittance is always positive but the sign of the imaginary part, ie, the susceptance, depends on the tuning of the compensation coil. Typically, the protection is set to operate with the additional resistive current component introduced by the parallel resistor of the coil. In the admittance measurement the increase of resistive current is directly measured in the real part of the admittance, ie, in the conductance.

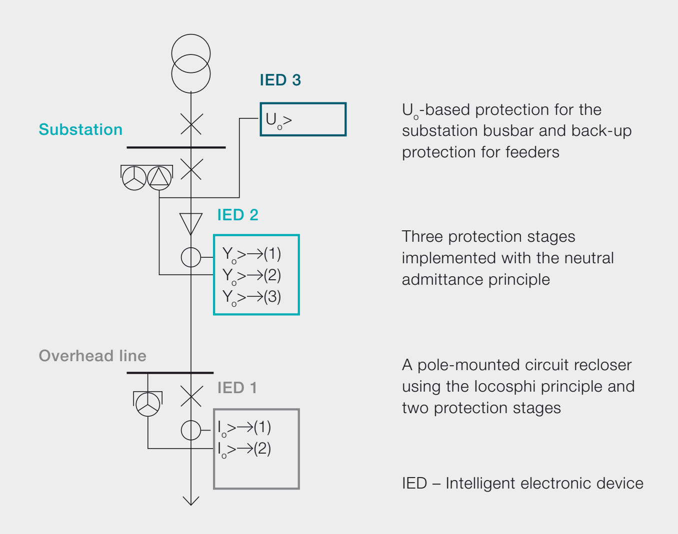
The fundamental principle of operation of admittance-based earth-fault protection is based on discriminating between the neutral admittances resulting from inside

3 Examples of real (Re) and imaginary (Im) admittance characteristics




The shaded area is the non-operate area, ie, protection operates when the calculated admittance is outside the boundary line(s).

4 Example protection diagram for an MV feeder protection applying both neutral admittance and traditional earth-fault protection functionality




and outside faults. The protection operates, ie, trips the circuit breaker, when inside fault admittance is measured but not when outside fault admittance is measured. This condition is characterized by operation boundary lines that may be circular or composed of single or multiple lines. Protection operates when the calculated admittance point moves outside these lines → 3.

The neutral admittance principle is flexible enough to be applicable to all types of high-impedance earthed, unearthed and compensated networks, including feeders with distributed compensation. These latter devices are becoming more common as weather-vulnerable overhead lines are replaced by underground

The admittance principle is applicable to all types of high-impedance earthed networks, including feeders with distributed compensation.

cables. These cables multiply the earth-fault current produced by such feeders, which typically calls for local compensation implemented by distributed coils. The distributed coils may be problematic for conventional earth-fault protection schemes as their characteristics cannot be easily adapted, eg, if the feeder configuration is significantly changed.

The principle's flexibility also provides enhanced protection during restriking earth faults as there is a bigger margin before false operation can occur [2].

### Fully compatible with traditional earth-fault protection

As in traditional earth-fault protection, the neutral admittance principle uses the residual overvoltage condition as a general start criterion to define basic protection sensitivity. This allows intermixing with traditional principles, convenient when various protection principles are used in one substation distribution area → 4.

### Further improvement of the admittance principle

Traditionally, earth-fault protection is based on residual current and residual voltage phasors that are calculated as soon as the earth fault is detected. Where the network is mainly composed of overhead lines, there may be a high-magnitude, healthy-state residual voltage present in the network due to untransposed phase conductors. Such asymmetry of the network affects the operate quantities so that the calculation result depends on, eg, the faulty phase. This dependence increases with fault resistance and may negatively affect earth-fault protection sensitivity. With the neutral admittance principle, it is possible to

With the neutral admittance principle, it is possible to remove the effect of network asymmetry from the measurement results.

From the protection perspective, the problem of harmonics can be turned into an advantage.

remove the effect of network asymmetry from the measurement results. This is accomplished by using so-called delta quantities: Pre-fault values of the residual current and voltage phasors are subtracted from the values measured during the fault before calculating the neutral admittance. The appropriate algorithms can easily be implemented in modern intelligent electronic devices (IEDs) [1].

### A problem becomes an opportunity

More higher-order harmonic components are appearing on MV networks due to increasing numbers of harmonics-generating loads and various nonlinear elements. As a consequence, there are also significantly more harmonics in the fault current during a single phase-to-earth fault.

As the compensation coil only compensates the fundamental frequency component of the capacitive earth-fault current, the other frequency components remain. Traditionally, these components have been considered to be disturbances that need to be filtered out. However, neutral-admittance-based earth-fault protection can take advantage of these harmonics to improve the discrimination between fault and nonfault conditions [3]. In modern IEDs, the harmonic admittances can be easily calculated and added to the fundamental frequency admittance in phasor format, making the discrimination between fault and nonfault conditions even more distinct.

### Years of positive experience

Since its invention, the neutral-admittance-based earth-fault protection approach has spread from Poland to other European countries. It can be applied to standard directional earth-fault protection, but also to high-impedance and intermittent earth-fault detection. Recent advances in the topic have been made by ABB in cooperation with Finnish power utilities. Based on extensive field tests, it can be concluded that the technique does indeed have sensitivity superior to that of traditional earth-fault protection principles. With proper settings and accurate measurements, earth faults with fault resistances of up to 10 kΩ can be detected [2].

In comparison with traditional methods, neutral admittance protection provides several attractive features, including improved sensitivity and security for both continuous and restriking earth faults. Further, it is applicable universally, including in networks with distributed compensation, thus also making the principle a safe choice for future smart grid applications. Finally, the protection settings are easily derived from the basic system data, which enables simple and practical optimization of the operation characteristic.

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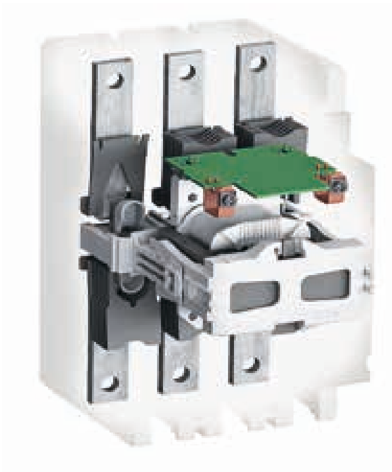
# Clean contact

## Contactor technology for power switching and motor control

GUNNAR JOHANSSON – Electric contactors are nearly as old as electrotechnology itself – a fact ABB can attest to, having produced low-voltage equipment for over 100 years. Now, however, innovation and new technology are breathing new life into contactors and are eliminating many of the problems that traditionally dogged this workhorse of the electrical switching world. ABB's new-generation AF contactors are paving the way.

1 Contactor schematic



ABB's new contactors utilize software and an electronic circuit in combination with a specially designed magnet to quickly build up a high contact force.

A contactor is an electrically controlled switching device that works much like a relay, but for higher currents. Unlike the circuit breaker, which is another type of switching device, the contactor cannot break short-circuit currents, though it can perform many more operations. Traditionally, contactors are for starting and stopping electrical machinery. The most common contactor type is the three-pole contactor, used to make, conduct and break the current in a three-phase system.

Contactors are built around a contact system that connects to the main circuit. Adjacent to this contact system is a breaking chamber containing various devices that improve breaking performance. The moving contacts are operated by a contact bridge with springs that provide contact force in the closed position. The movement is accomplished by an electromagnet that is enclosed by a coil ➔ 1.

A rear-mounted circuit facilitates combination with other switching devices and prevents the main circuit cables blocking access.

**Title picture**
Ever since electrotechnology was first introduced into the world of industry, contactors have played a vital role. New ideas have now overcome traditional drawbacks, allowing a new generation of contactors to be launched.

## Simple product concept

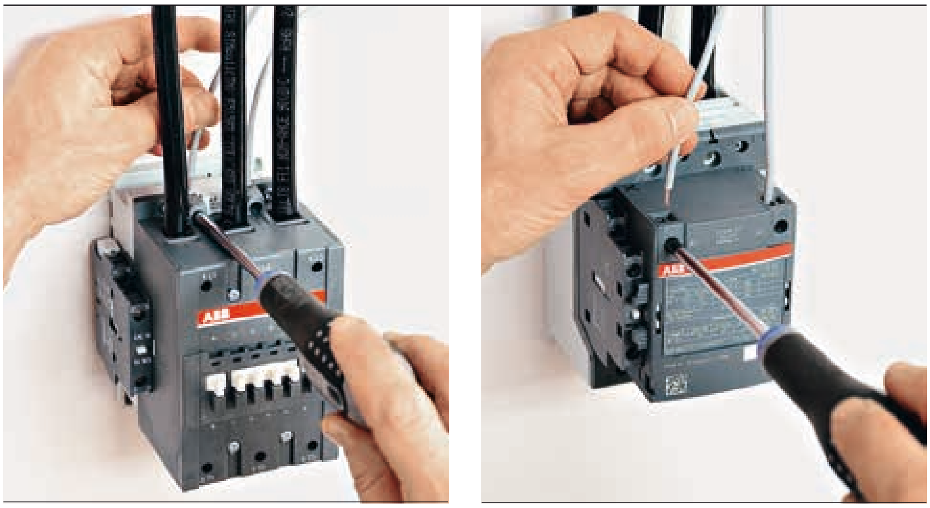
Large contactors from ABB differ significantly from competitors' by having the main circuit located at the rear. Launched about 10 years ago, this approach has now been proven in the field. This configuration facilitates combination with other switching devices, primarily circuit breakers, and prevents the main circuit cables, which are thick and rather stiff, from blocking access ➔ 2.

The cost of the electronics has been brought down to a level that makes these electronically controlled contactors comparable in price to conventional ones. Assembly costs are low as the electronic module easily snaps into the contactor.

## Less raw material

When contactors make or break large currents, arcs are generated. These

2 Placement of circuit at the rear eases access



2a Older contactor with main circuit in the front

2b New contactor with main circuit in the rear

The cost of these electronically controlled contactors is comparable to that of conventional devices.

erode the contact material and this erosion determines the contactor life. A high-grade silver alloy is usually the principal contact constituent. As silver is expensive, increasing the contact bulk to increase contact life is impractical, so ABB has devoted much research to finding other ways to extend contact life.

Several approaches have emerged:
- Improving contactor movements by using an electronic control circuit
- Using software solutions that reduce contact wear
- Designing new magnets that allow higher contact forces
- Introducing new breaking chambers that better remove and quench arcs
- Tuning the contact material manufacture and composition to give high durability

## Closing contacts

When switches close, small, short bounces sometimes occur before the contacts settle in the closed position. This so-called contact bounce causes minor, erosive arcs to form. As the current at this point is low, contact bounce is not so important. Far more important is contact lift.

Contact lift happens a little later, when the current is high ➔ 3. The contacts are then usually in the correct position but there are factors, for example, the high switching current, that can separate them, causing arcs. As high currents are flowing, erosion is severe ➔ 4. Also, vibrations, which arise from the closing contactor magnet, can interact with the separation forces to cause contact lift. Therefore, contacts must be held tightly closed so as to resist any possible separation forces. To do this, ABB's new contactors utilize software and an electronic circuit in combination with a specially designed magnet to quickly build up a high contact force. The circuit also provides a measured and controlled movement that minimizes vibrations. Contact lift is rare and erosion on making is thus minimized.

## Opening contacts

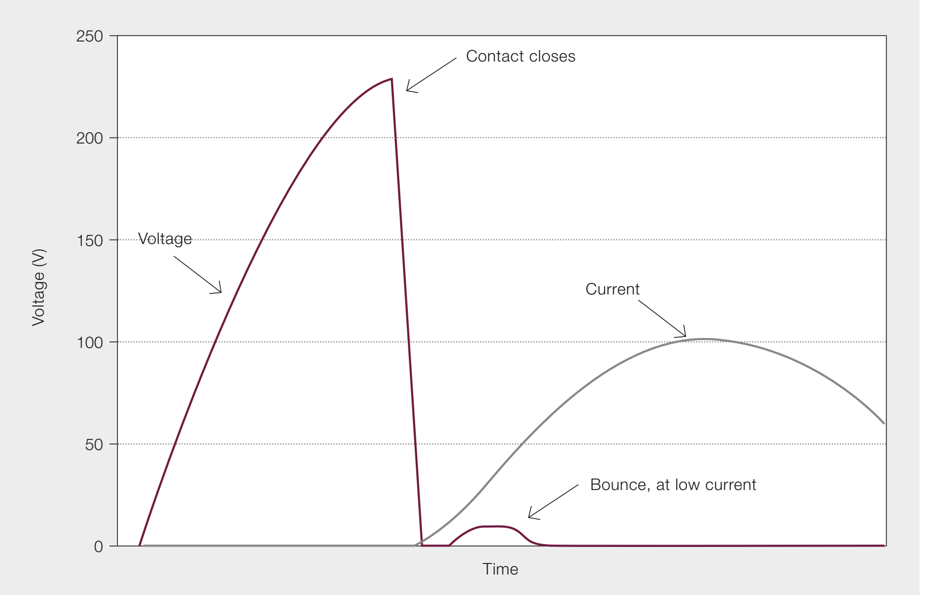
When breaking high currents (over 100 A), the arc has to be moved away quickly from the silver contact material in order to limit erosion. The erosion also has to be distributed as evenly as possible between the different phases.

In order to move the arc away from the contacts, conventional technology is used. A steel plate encloses the contact and draws the arc away. Designs are now carefully calculated and optimized by using simulation tools. Some old truths have been questioned and disproved while others have been exploited to their full potential.

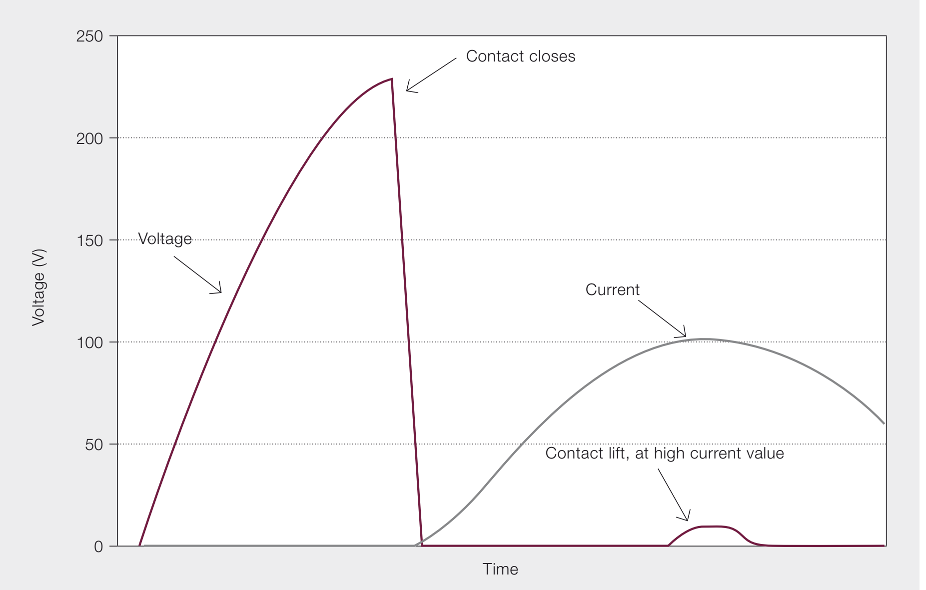
The control circuit, together with the coil and magnet, can, unfortunately, cause the contactor phases to be loaded unevenly as the voltage at the control circuit is often related to the main circuit and a certain amount of synchronization can occur between the moment of switching and the voltage phase. The load will then not be evenly distributed between the contactor's phases and the

A silver and tin oxide mixture, with dopants, provides a good contactor material.

**3 Contact bounce and contact lift**




**3a Contact bounce typically occurs at low current values and is not problematic.**




**3b Contact lift occurs at high currents and can cause severe contact erosion.**

phase most used will wear soonest and, in so doing, determine the lifetime of the entire device. It is better to distribute the load evenly between the phases and equalize contact erosion. The ABB software and electronics do exactly this by eliminating synchronization. Significant improvements in longevity have resulted. The method has a patent pending.

## Contact material

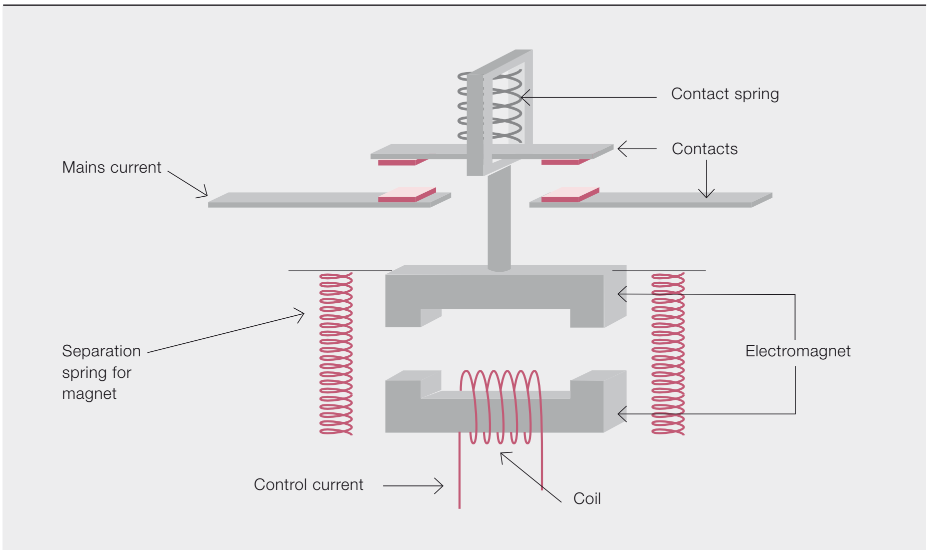
The actual contact material used and its production method have a great influence on erosion. In the past, alloys of silver and cadmium provided very good performance, but cadmium has long since been prohibited. Pure silver contacts would be excellent were it not for the fact that they weld together and rapidly erode. A silver and tin oxide mixture, with dopants, however, provides a good contactor material. As this material is so critical, ABB uses a very carefully determined mixture and the most advanced manufacturing processes to produce it.

## Reliability is key

Reliability is the contactor quality most valued by customers. ABB has devoted much meticulous design work and extensive testing to realizing contactor products that meet the highest reliability requirements. The quality of the control circuit is critical.

4 Contact lift at making – snapshot from a movie. The arc consumes contactor material.

5 Conventional and well-proven control circuit




The circuit provides a measured and controlled movement that minimizes vibrations.

## The control circuit

A contactor's control circuit is built around a split electromagnet that works with a spring system. The magnet is activated by a current flowing through a coil that causes the two magnet halves to attract each other. This attraction closes the magnet and, via the spring system, it also closes the contacts and provides contact force. When the magnet is deactivated, it opens – along with the contacts, interrupting the main current → 5. This basic principle has been used for over 100 years and no one has yet presented a more competitive alternative. ABB and its main competitors use this simple, proven and reliable solution to make, conduct and break large currents.

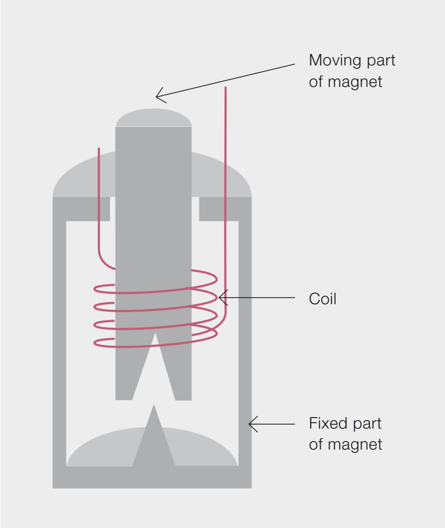
ABB's AF contactors use a patented microprocessor-controlled circuit that ensures the coil current is correct, regardless of voltage fluctuations.

The method, however, does have shortcomings:

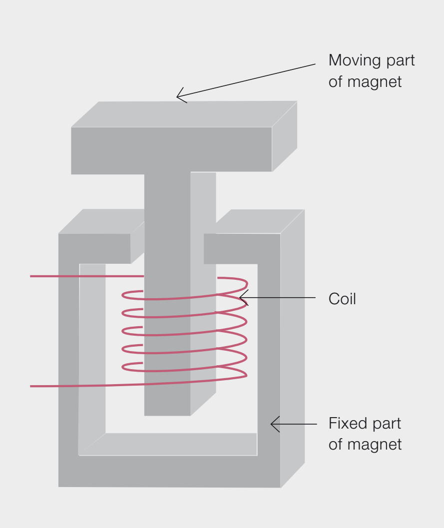
- Sensitivity to voltage variations. Variations in the supply voltage cause changes in the coil current. These have a quadratic effect on the magnetic force. In unfortunate cases, contacts can suddenly open and close, causing failure of the device.
- Most users will want to use an AC control voltage, for instance 230 V at 50 Hz. The magnet must then be both big and complicated to keep up the force at the control voltage zero crossings.
- The power consumption of the circuit is high, especially when it is supplied with an alternating voltage.
- The tolerance requirements of the surface at the magnet's poles are extremely high. During heavy use, the dimensions can change, causing a deterioration in the magnetic force.

The ABB software and electronics distribute the load evenly between the phases and equalizes contact erosion.

6 Section of cylindrical magnet




7 Magnet with T-shaped moving part




Modern technology and innovative design, however, now deal with these issues.

## New in control circuits

ABB's new AF contactors use a microprocessor-controlled circuit with patented algorithms that ensure the coil current is always correct, regardless of voltage fluctuations. Thus, both the magnetic flux and the contact forces are optimized. The circuit also converts AC to DC voltage. This reduces power requirements, provides smoother magnetic force and dispenses with zero crossings. It also enables a smaller, simpler and more reliable magnet to be used. Mechanical and electrical wear are minimized.

Because zero crossings are eliminated and the coil current is controlled, old and well-proven magnet designs that otherwise would have severe limitations can be resurrected and fully exploited.

In the smallest AF contactors, a cylindrical magnet with a movable piston is used together with pole surfaces that are conical ➔ 6. This is a very compact and low-power arrangement. It is so effective and requires so little power that the contactors can be operated with a weak power supply such as a transistor output. The larger AF contactors use a magnet whose moving and fixed parts are T-shaped and U-shaped, respectively ➔ 7. This is also a compact and low-power solution. Both types of magnet take advantage of the fact that only DC exists in the coil.

Contactor design, though over 100 years old, has become a new and engaging field of product development – thanks to new technology and innovative thinking. Further enhancements to simplify the design, increase the reliability, improve logistics and optimize the service of this stalwart of electrical switching are in full flow.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# Deep breaths

## Optimizing airflow for underground mines

MICHAEL LUNDH, JAN NYQVIST, MATS MOLANDER – From August to October 2010, the world held its breath. Trapped 700 m below the surface of the Atacama desert in Chile were 33 miners. Their entrapment focused minds on the fragile essentials of life: environmental temperature, food, water and air. As commodity prices rise, previously "inaccessible" resources become economically viable. But worthwhile market prices and investment thresholds alone do not overcome the physical and technical challenges that harvesting these remote resources present. Physical limitations remain, which define what can be reasonably and, more importantly, safely reached. But new technologies continue to appear and evolve, allowing humans to continually redefine these limitations. New frontiers are reached, but this is only possible by ensuring that the support systems for life keep pace.

Ventilation consumes a significant amount of energy, typically 100 GWh/year which can be as a much as 50 percent of the total energy consumption for underground activities.

1 A ventilation duct in an underground mine

Underground mines today often operate at depths of down to 2.500 m with some gold mines, even down to 3.600 m. That's as far below the surface of the earth as La Paz, in Bolivia, is above it. The trend is that mining in the future will be mainly underground and at even deeper levels, in remote locations. The mining industry, characterized today by a high degree of mechanized mobile tasks in a harsh environment, is actively seeking automated solutions to meet the future demands of safe, sustainable and productive operations.

Fresh air must be distributed to the production areas where mine personnel are located and the incoming air might need to be heated or cooled.

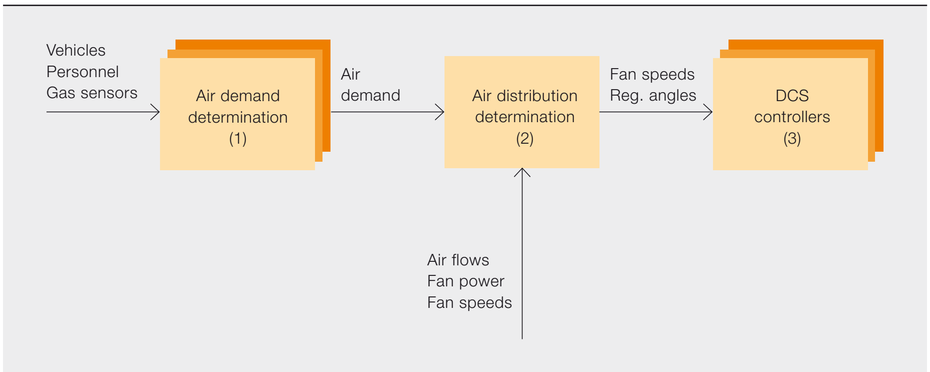
Underground air is polluted by hazardous gases such as CO, $NO_x$, and $CO_2$ from diesel-driven equipment and blasting, and also radon and methane (in coal mines) can be found naturally in the ground. Proper ventilation is needed to assure a healthy working environment in an underground mine → 1. The purpose is to distribute fresh air to the production areas where mine personnel are located. It is a support function that interacts highly with production. Ventilation consumes a significant amount of energy, typically 100 GWh/year which can be as a much as 50 percent of the total energy consumption for underground activities.

Today, main fans on the surface feed the mine with fresh air, which is distributed underground where needed by fans and/or air regulators. The incoming air might need to be heated or cooled. The state-of-the-art technology for control is ventilation on demand (VoD); however, many mines are not controlled at all. But even VoD has drawbacks: There is no feedback control and VoD uses a complex or weak fan/air regulator relation model.

ABB now offers a new unique method for mine-wide coordinated control of the fans and the air regulators, to achieve an energy-optimized and reliable solution that automatically feeds the mine with

**Title picture**
One third of the world's mined copper comes from the driest desert on earth, the Atacama desert in Chile. Photo courtesy: © 2013 Michael Vogel.

2 Overview of mine ventilation control function




Through automated system identification, based on operational data or triggered experiments, the simple dynamic relation model can easily be adjusted for the new conditions.

the required air. The solution is based on empirical models and relies on feedback from air sensors, which can be, for example, gas, flow or temperature sensors. Multivariable models describe how changes in the speed of fans affect both the airflow and the pressure over fans. The parameters in the models are obtained empirically from operational data which makes the model easily adaptable for new conditions.

### Applying MPC

Advanced process control has been applied successfully in many areas, eg, in chemical processes and in refining.

Multivariable models describe how changes in the speed of fans affect both the airflow and the pressure over fans.

The most widespread approach is model predictive control (MPC) [1], the origins of which can be traced back to the 1970s.

A model predictive controller utilizes an explicit model to predict the future response of a plant. Based on this it is possible to determine control signals that affect the plant so that the desired response of the plant is obtained. Since the desired behavior is often a trade-off between conflicting goals, an optimization problem is formulated to find the "best" solution. A dynamic model that describes the plant is essential. Accomplishing a dynamical model can be time consuming: In normal process-industry advanced process control (APC) projects, the biggest effort is spent on finding a sufficiently good model. Normally the modeling consists of a plant testing phase where the inputs are agitated to excite the plant outputs. Both inputs and outputs are logged and these logged signals are then used by mathematical methods to determine a model. This is referred to as system identification [2].

The new approach for mine ventilation is inspired by the MPC methodology. The underground mine challenges the MPC technology because the mine is continuously changing. New tunnels are opened for production and out mined tunnels are closed. New fans and ventilation ducts will be added when the mine is developing. There can also be unplanned changes of the structure, eg, after blasting. Through automated system identification based on operational data or triggered experiments the simple dynamic relation model can easily be adjusted for the new conditions.

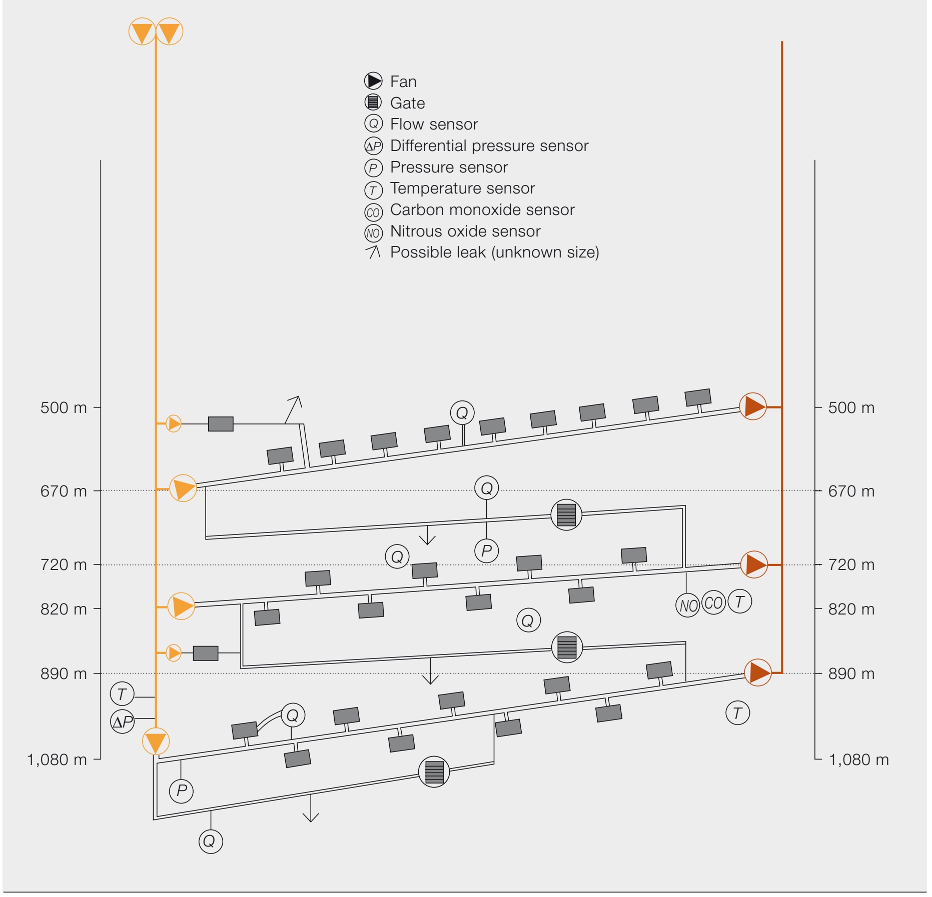
### Overview

The new approach for mine ventilation has similarities to the VoD currently in use. The structure can be divided into three levels for both types of solution. ➔ 2 shows an overview of the function.

1) The top level determines the actual air demand in various airways in the mine. The demand is obtained from the presence of vehicles and persons in particular locations. Demand may also be determined from sensors, measuring concentrations of different gases in the mine. There may also be some airways where it is of interest to keep the flow as

> The optimized fan speed is determined from the air demand in various airways, properties of the fans and motors driving the fans.

3 A schematic sketch of the mine used for testing




low as possible, eg, to control access ramp flows.

2) The second-level functionality determines the distribution of air by optimizing the speed of fans that drive the air through the mine. The optimized fan speed is determined from the air demand in various airways, properties of the fans and motors driving the fans. The second level may also include the opening angles of the air regulators that are used to control the air flow. The fan speeds and the air regulator angles are determined in order to minimize the actual total power used for ventilation while still satisfying the air demand. This minimization is based on a model that relates changes in fan speeds to changes in air flow and actual used power.

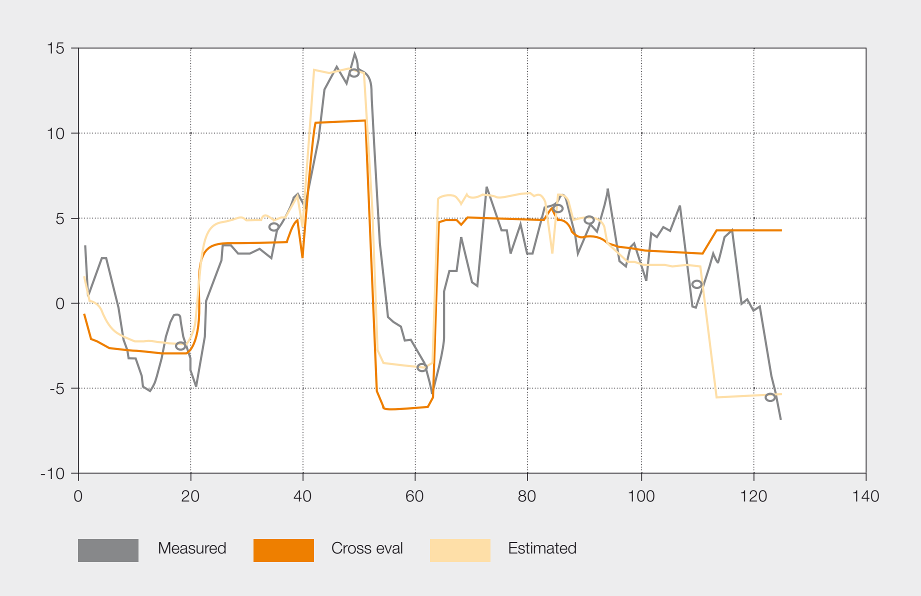
3) The optimal fan speeds and air regulator angles are then used as set-points for lower-level controllers in the distributed control system (DCS).

In the new MPC solution, overall air distribution optimization is carried out on the second level.

## Modeling

The air distribution in the mine is affected by fan speeds and, if present, opening angles for dampers. These are the actuators in this control system. There is interaction between actuators and airflows in the mine. This means, for example, that a changed speed for a fan will not only affect the airflow in the airway where the fan is located, but also affect airflows in other airways. This interaction is what makes it difficult to control the airflows in

> The fan speeds and the air regulator angles are determined in order to minimize the actual total power used for ventilation while still satisfying the air demand.




an optimal way. It is therefore important that the model captures this behavior of the mine.

Dynamic multivariable models could be used to describe the mine. Such models are used in many applications, eg, in the refining industry. A drawback with these models is that substantial effort is required to obtain a model. This is undesired here since the shape of the mine is consistently changing, through extensions, and accidental new paths for air flow may occur due to blasting. It is not practical or useful to spend weeks building a new accurate dynamical model of the mine each time a change occurrs.

In this case a simple static multivariable model, which is able to capture the essential interaction and impact from changes in the actuators, is used. The model is described on the incremental form

$$\Delta Q = H_q \Delta\beta$$
$$\Delta p = H_p \Delta\beta$$
$$\Delta E = H_e \Delta(\beta^3)$$

where $Q$ is a vector of measured air-flows, $p$ is a vector of pressures over fans, $\beta$ is a vector of fan speeds and E a vector of fan powers. $\Delta$ indicates changes between two samples. The coefficients in the matrices $H_q$, $H_p$, and $H_e$ are obtained from simple experiments, or from normal operational data that enables the automation of system identification.

The objective for the control is to maintain the desired airflow in various airways, while the power required to run the fans is minimized.

### Measurements

To identify the model of the mine ventilation system and to be able to use it for control, a number of variables must be measured:

– Gas concentration and/or air flows in various locations to be controlled
– Fan power of the fans to be controlled
– Fan speed of the fans to be controlled
– Pressures over fans

The controller adjusts the actual fan speed based on current demand.

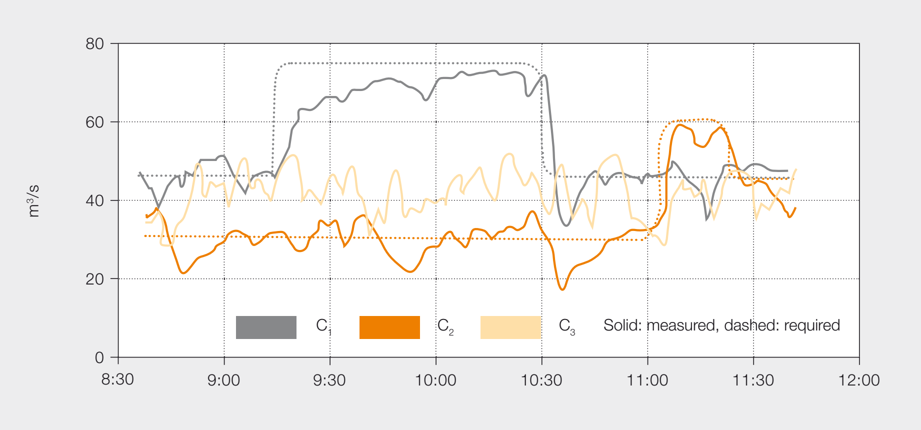
### Control

The objective for the control is to maintain the desired airflow in various airways, while the power required to run the fans is minimized. Airways that feed production areas with air must have an airflow that exceeds a required flow. Other airways may be requested to have airflows which should be kept as small as possible.

This can be formulated as an optimization problem where new fan speeds are determined to minimize the actual fan power.

Vehicles are entering and leaving production areas all the time, meaning the air demand for the airways to these production areas changes.

5 System adjusting the airflow to a step change of demand




During minimization, constraints on airflow and on differential pressures are taken into consideration:

$$Q_{lo} \leq Q(k) \leq Q_{hi}$$
$$\Delta p_{lo} \leq \Delta p(k) \leq \Delta p_{hi}$$

In addition, there are limitations on the fan speeds:

$$\beta_{lo} \leq \beta(k) \leq \beta_{hi}$$

This optimization problem is solved on a cyclic basis where new fan speeds are calculated. The initial values for each optimization are provided by filtered values of the measured signals.

## Field tests

The new method of controlling the mine ventilation in an optimized way has been tested in an operating underground mine. The mine was already equipped with an ABB VoD system connecting all the fans and sensors.

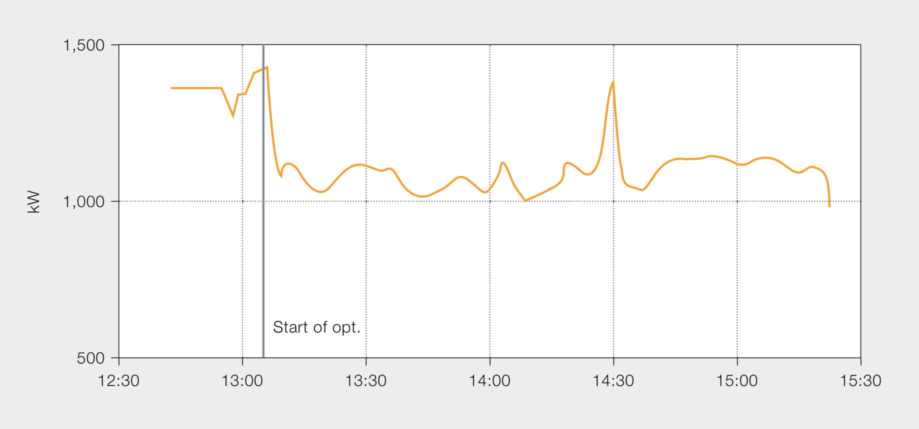
Despite the evolving nature of the mine there is no break in the efficiencies from which the mine benefits.

A schematic sketch of the mine is shown in ➔ 3. The controlled area of the mine consists of three production levels from a depth of 500 m down to 1.080 m. There are two surface fans at the air intake, plus one fan at the inlet and one at the outlet on each production level. The orange line represents incoming fresh air and the brown line outgoing polluted air. In each level, and in the access tunnels between the levels, air speed is measured with ultrasonic flow sensors. The locations of the sensors are marked with a Q in the sketch. For each fan the static pressure rise is also measured.

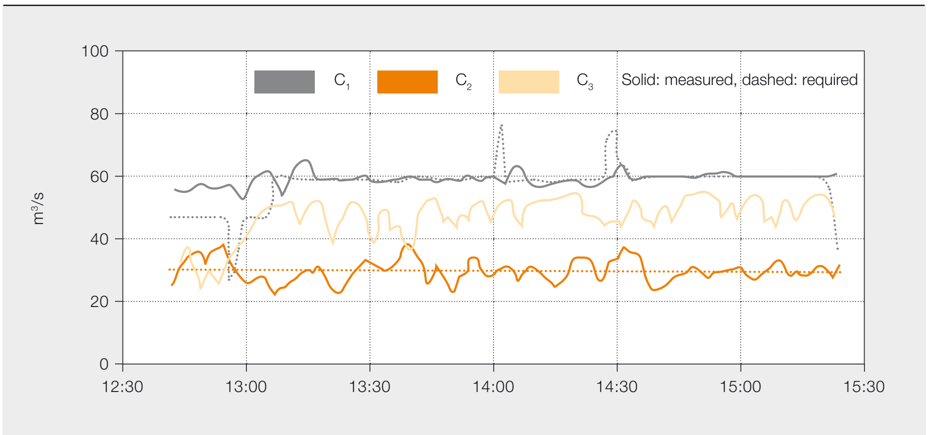
Vehicles are entering and leaving production areas all the time, meaning the air demand for the airways to these production areas changes, and the current VoD system for ventilation will change the fan speeds accordingly. This will provide the necessary excitation to identify the model. After appropriate filtering and the removal of high-frequency variations, the static models of the mine, described above, are identified by the simple least-squares fitting method. An evaluation of two such models is shown in ➔ 4. One of the models was identified using the same data as the measured data plotted in the figure (Estimated) and the other (Cross eval) was identified using a completely different set of data.

The fan optimizer, based on the identified models, was tested over two days where the ventilation of production levels was controlled by the optimizer. The result, as recorded by ABB's System 800xA during the test, is shown in ➔ 5. The chart shows how the system adjusts the air flow, in the first level of the three level mine, to a step change of demand (solid grey line) and the air flow in the second level to a demand step change (solid dark orange line).

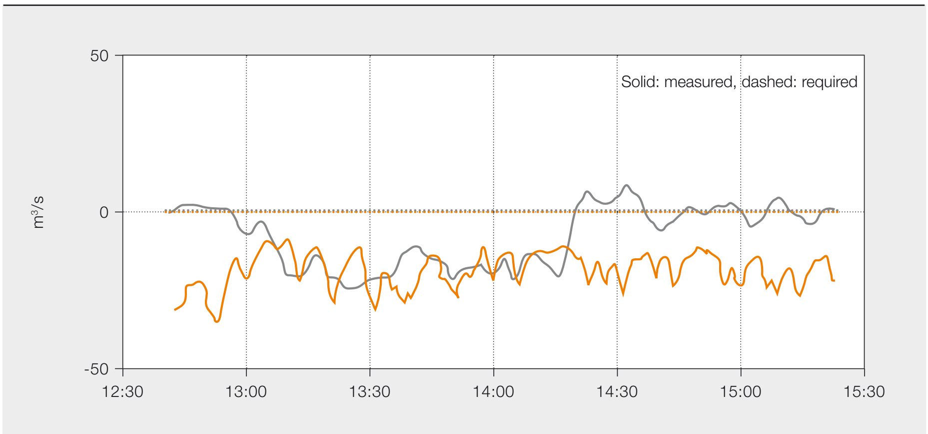
## 6 Operation plot of the model showing reduced fan power




6a Total fan power




6b Cell flows




6c Access ramp flows

A plot of another registration recorded during the operation is shown in ➔ 6. The plots show how the optimizer can substantially reduce the fan power while fulfilling the air flow demands in the airways. The tests have shown a possible reduction of fan power of 30 to 50 percent compared with the existing system in operation, while maintaining the same airflows.

### Air achievements

The field tests indicate that applying the simple empirical models on an underground ventilation system one can achieve:

- Automatic control of a healthy working environment in an underground mine adjusted to current air quality demand
- Automatic adjustment to new working conditions when the mine is developing
- Significant fan power reduction by optimizing distributed loads on existing fans
- Robust and reliable automated ventilation through feedback control

The working environment benefits from receiving optimized air flows that best fit the activity in that location.

Applying these dynamic empirical models to mine ventilation systems brings multiple benefits. Not only does the mine owner or operator benefit from reduced running costs, but the working environment benefits from receiving optimized air flows that best fit the activity in that location. Despite the evolving nature of the mine, the existing model keeps pace, ensuring that air and fan optimization is continuous. That also means there is no break in the efficiencies from which the mine benefits, even in some of the harshest and most remote working environments.

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# Top gear

## Technology to improve mining productivity

LEN EROS, MIKE SMALE, DAVID KEECH – High demand for basic raw materials has put pressure on the mining industry and created a trend toward larger mining operations with higher productivity targets. However, how do these huge mining operations produce more – under challenging environmental conditions – while at the same time containing costs? One way is to partner with a company that can offer not only engineering expertise but also robust, innovative equipment engineered for mining's unique production needs. On the equipment side, ABB has a broad range of field-proven products that are used in conveyor belts, hoists, crushers, mobile haulage machines, ventilation fans, etc. Many of these require gearing and it is essential to have the very best gear-reducing products if cost, maintenance and production targets are to be achieved.

Technological developments have made it possible to mine ores of declining grades and more complex mineralogy while minimizing cost increases.

The global mining industry is huge: By the end of 2012, there was over $400 billion of investment in capital programs outstanding [1]. And keen competition makes mining productivity very important. Most productivity increases in the past century have been achieved through more efficient mineral processing and the use of larger-scale equipment. Thus, technological developments have made it possible to mine ores of declining grades and more complex mineralogy while minimizing cost increases.

Today, companies such as ABB that can deliver complete technical solutions to the mining industry have an advantage due to the necessity to competently address the sheer scale and complexity of modern processes producing material at ever-faster rates.

ABB has not only industry expertise but also a broad range of field-proven products that live up to the specific performance and efficiency requirements of mining operations. ABB's products are used in equipment such as conveyor belts, hoists, crushers and ventilation fans, as well as mobile haulage machines and systems. Because of the harsh and demanding nature of mining processes, robustness and reliability are key product requirements.

Companies that can deliver complete technical solutions have an advantage as they can competently address the sheer scale and complexity of modern processes producing material at ever-faster rates.

Power savings have an impact on mining companies' bottom line, too, so energy-efficient products hold an important advantage. More broadly, mining companies benefit greatly from a partnership that can supply a total electrical and mechanical solution.

### Products giving lower total cost of ownership

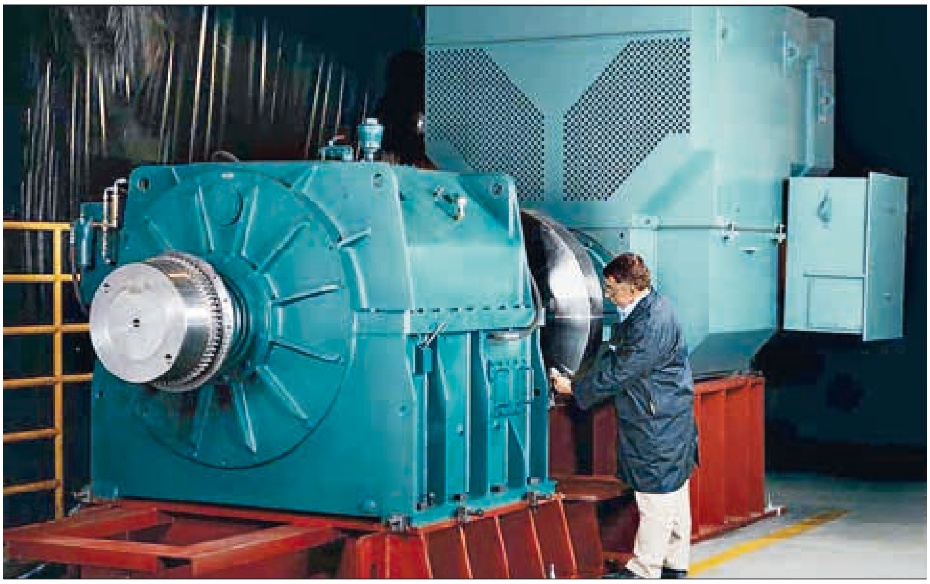
ABB's portfolio of electrical products includes a full range of motors, including

**Title picture**

To keep at the forefront of large-scale, intensive mining, modern mining enterprises form tight collaborations with engineering partners who have not only expertise, but also a comprehensive range of products suitable for the tough conditions encountered in excavation operations.

Power savings have an impact on mining companies' bottom line, so energy-efficient products hold an important advantage.

1 Fully assembled drive system package featuring a 2,500 K Dodge CST, a 2,500 hp Baldor Reliance motor, an optional 3,150 pound fly-wheel and high- and low-speed couplings



explosion-proof mining duty motors, and low- and medium-voltage variable-speed drives (VSDs) of many types. ABB's mechanical portfolio encompasses large gearing, controlled-start transmissions, mounted bearings, couplings and pulleys. Offerings also include power distribution and power conditioning systems and switchgear to direct electrical energy to the mining equipment.

ABB offers the most complete line of large AC and mining industry motors in the world. Baldor-Reliance® stock and custom motors are available up to 11 MW (15,000 hp), while induction and synchronous motors are available up to 65 MW (87,000 hp). This offering includes both NEMA (National Electrical Manufacturers Association) and IEC (International Electrotechnical Commission) configurations, which reassures customers they will get a motor that meets frame, enclosure and duty cycle standards for specific applications. Mining industry motors are designed with an extra-tough external construction to suit the rough operating environment, along with bearings and sealing systems that extend life.

The Dodge CST is designed to deliver superior motor-load sharing to minimize the loads and stresses on all conveyor components.

ABB also delivers the latest in conveyor drive technology in the form of gearless conveyor drive systems. These utilize low-speed synchronous motors with frequency converters and reduce the overall component count, thus increasing system reliability and reducing maintenance requirements.

### Gear reducers

In conventional geared drive systems, motor power can be delivered to the conveyor system with ABB's various proprietary gear reducers, including the controlled start transmission (CST) and MagnaGear XTR® reducer, both specifically designed for mining applications.

### Dodge® CST

The Dodge CST is designed to provide motor load sharing to minimize the loads and stresses on all conveyor components. In essence, CST is a two-in-one gearbox that combines a planetary gear reducer with an integral wet clutch system. When coupled to an AC induction motor, the CST gearbox converts the motor's high-speed, low-torque input to a low-speed, high-torque output. Torque ratings up to

2 A 210 K MagnaGear XTR operating on a 365 m long conveyor with a 26 m lift

The largest installed base is in China, with more than 2,000 CSTs in operation.

400 kNm (3,500,000 lbf in) are available. Maximum motor power is available throughout the full operating range. The clutch unit absorbs shock loads and protects the motor, gearbox, bearings, pulleys, conveyor belts and splices. The rugged design delivers total control of the most difficult high-inertia loads, such as long conveyor belts and conveyors with multiple synchronized drives → 1.

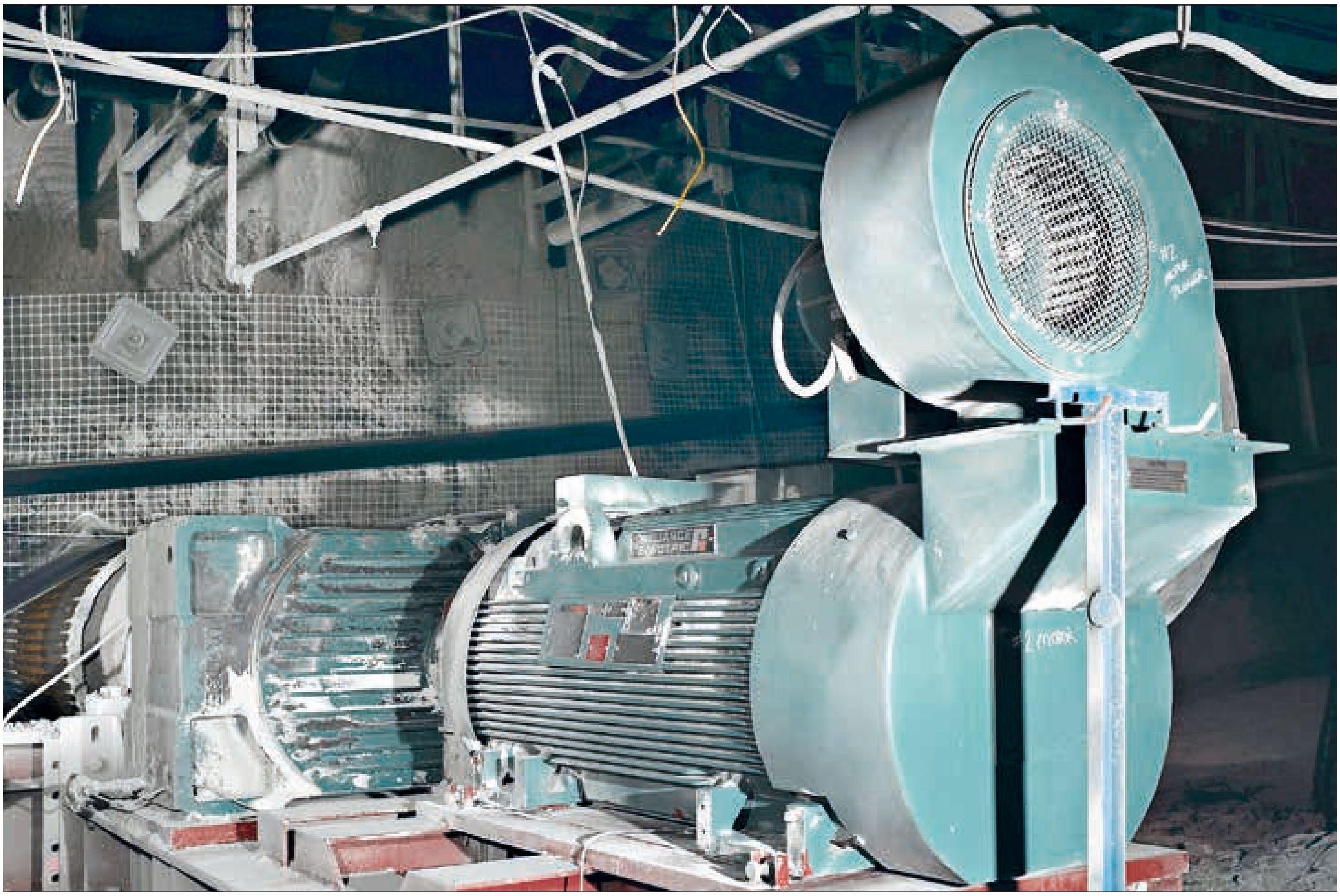
The wet clutch system, located internally on the output side of the gearbox, allows the motor to be started under no-load conditions. As the PLC-based control system gradually engages the clutch, the output shaft begins to rotate and smoothly accelerates to the desired driving speed in a predetermined time.

Serviceability is also a key factor in drive system selection. CST systems are simple to operate and maintain without

The rugged design delivers total control of the most difficult high-inertia loads, such as long conveyor belts and conveyors with multiple synchronized drives.

the high degree of technical expertise required by more complex control packages. This is especially important in remote locations that rely on local resources for service and maintenance.

3 A 700 K MagnaGear XTR reducer connected to a 700 hp Baldor Reliance mining industry motor in an underground mine



By 2012, more than 3,000 CSTs were installed worldwide, and there are six currently being installed in a copper mine in South America – one of the most complex installations of its type. At an elevation of 5,000 m, it will include four 2,250 kW (3,000 hp) CSTs and two 1,400 kW (1,900 hp) CSTs, with bases and high-speed brakes.

> The Dodge MagnaGear XTR is an innovative speed reducer widely used for heavy duty applications requiring torque ratings up to 240 kNm.

For another customer, ABB provided a design that offered 20 percent savings on the capital cost of the drive, with additional savings on the installed cost of the conveyor system. It was substantially lower in cost than the specified design, but delivered more total power. Using three 1,875 kW (2,500 hp) drives, with nearly 3.7 km of loaded belt, this mine has produced as much as 100 million tons of coal annually.

The largest installed base is in China, with more than 2,000 CSTs in operation. One company has 400 CSTs that are used across 17 coal mines with a total area of 10,000 km$^2$. Equipped with sophisticated remote monitoring, this system has achieved an availability rate of 98 percent.

### Dodge MagnaGear XTR

The Dodge MagnaGear XTR is another innovative speed reducer widely used for heavy-duty applications requiring torque ratings of up to 240 kNm (2,100,000 lbf in) → 2–3. In sizes over 44 kNm (390,000 lbf in) it incorporates a planetary gear design, which is a compact, durable and economical solution for high-torque applications. MagnaGear

XTR reducers can be used with a wide variety of softstart and control systems, including electronic softstarts, VSDs and fluid couplings.

MagnaGear XTR reducers are designed to meet or exceed AGMA (American Gear Manufacturers Association) minimum bearing life. The bearing life, in fact, is more than double that found in many competitors' reducers. Incorporated in this design is a tandem sealing arrangement and efficient cooling system that offer low-maintenance operation. MagnaGear has an associated line of accessories tailored to particular applications, including baseplates, swing-base mounts, tunnel drive configurations, torque arms, internal lift-off style backstops, couplings and electric fans.

Dodge mounted bearings set the standard in the industry. The ISAF and metric ISN types offer the only push/pull adapter mount system that cuts installation time, while the fully concentric shaft attachment virtually eliminates fretting corrosion. A Dodge large-bore pillow block bearing for larger applications features a patented hydraulics-assisted, adapter-mounted installation and removal system. Not only are these bearings quickly installed and removed, they are factory assembled, sealed and lubricated. ABB's mechanical power transmission offering is completed by engineered pulleys and a variety of couplings.

## More than products

As engineering expertise within mining companies is often constrained, they often partner with manufacturers that can not only offer appropriate products, but also engineering expertise. ABB mining experts, along with Baldor's mining industry team, understand the challenges the industry faces and know the best ways to apply products and packages to deliver successful solutions.

The design of conveyor drive systems is a good example of the joint approach. The goal here is to design a conveyor that transports as much material as possible with best performance and reliability. The challenges are formidable: The trend in the industry is to use conveyors to transport bigger loads over longer distances. A conveyor may have to transport as much as 30,000 tons of material per hour over distances of 10 to 20 km, 24 hours a day. Early in the design process, the team uses an industry standard program ("Belt Analyst") to configure the drive system with the correct output power and optimize the selection of motors, VSDs, gearing, bearings, couplings and pulleys.

ABB stays at the forefront of mining technology by collaborating with a number of universities and industry bodies around the world. Research projects have covered the modeling of next-generation motors and issues such as heat transfer and the cooling of motors. In relation to standards development, the company has members on various NEMA, IEC, IEEE and CEMA (Conveyors Equipment Manufacturers Association) technical committees.

With such an all-encompassing range of products and such extensive industry experience, ABB can solve customer problems by delivering power-matched solutions with the right motor, control system, gearing, bearings, couplings and pulleys. ABB will continue to identify and develop industry-specific application solutions to deliver benefits to end users with the aim of reducing total cost of ownership through longer operational life and improved reliability combined with reduced downtime, higher operating efficiencies and energy cost savings.

MagnaGear XTR reducers can be used with a wide variety of softstart and control systems, including electronic softstarts, VSDs and fluid couplings.

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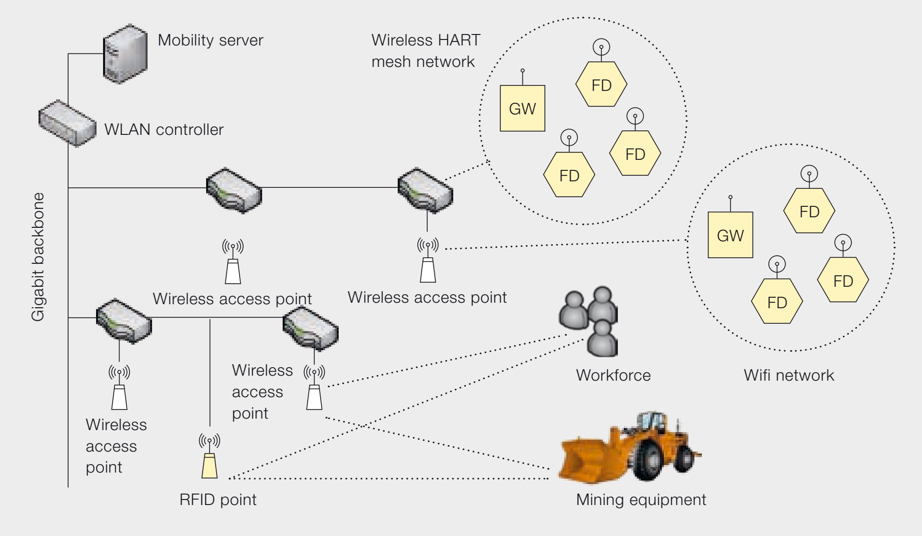
# Mine of information

## Integration of mobile equipment in underground mining

STEFAN L. SJOSTROM, KJELL G. CARLSTEN, KRISTER LANDERNAS, JONAS NEANDER – Unsurprisingly, most easy-to-find high-grade metal ore has already been extracted from the earth. This means that mining companies have to work harder to mine those remaining resources. There is, however, an area of technology that is less advanced in mining than in other industries that offers scope for significant increases in operational efficiency and profitability. This is the area of automation and data integration in the underground mining environment. The lack here of the technical sophistication seen in other industries means that optimization of the entire value chain, from mine to mill, often remains a pipe dream. However, ABB delivers systems that allow miners to optimize the utilization of underground mining equipment, increase mine productivity and reduce energy consumption.

1 A fully integrated network gives the operator a comprehensive view over the mining process. (FD = field device; GW = gateway.)




Mining was one of the very first industries developed by humans. Indeed, the oldest known mine is the Lion Cave in Swaziland, where pigment ingredients were mined and which radiocarbon dating shows to be about 43,000 years old [1]. Other mines, of similar age, yielded materials for toolmakers. Although mining has become highly mechanized over the last century, the uptake of technology in mines generally lags that in other industries, like oil and gas or pulp and paper. However, as ores and other desirable deposits become more troublesome to extract, increased automation and data integration become ever more important for successful mining.

In parallel, employee skill levels have to rise to facilitate this expansion in technology. Appropriately qualified operators are needed for product and process optimization, maintenance planning and environmental control. Overall, there will be fewer, more skilled employees and they will cover the entire value chain. It is likely that some of these operators will be able to control several mines – assisted by sensors and automated systems that deliver, via a communication backbone, the real-time information necessary for controlling each product and process ➔ 1. This integration allows the mine to optimize the utilization of underground mining equipment and increase mine productivity while reducing energy consumption. ABB's Extended Automation System 800xA platform and associated products facilitate such mine automation and data integration.

ABB's underground mining offerings allow real-time data from underground equipment of different types and manufacturers to be integrated into the System 800xA open process control system ➔ 2. This allows for better visualization and utilization of the equipment fleet, including machine location tracking, machine status reporting and relaying of actual operating environments underground. The design and implementation of such systems, including the selection and direction of information to drive business performance, is a critical competitive advantage.

## Mine automation

In general, many operations in a mine are reasonably well automated in themselves, but their integration with a master system is often poor or wholly absent. This results in suboptimization and an inhomogeneous perspective of the process.

A chief contributor to this deficiency is the lack of a versatile communication infrastructure, wireless or wired, in the underground mining environment. This makes it difficult to obtain an overview of, or full control over, the different operations in the mine. It also results in the inability to optimize the entire value chain, from the mine face to the mill. One reason for this deficit may be that the mining industry has not yet faced the same cost reduction and output optimization pressures as other comparable businesses.

The situation, however, is changing rapidly and the best way to bring about improvement is to introduce a flexible and multifunctional communication system into the underground mining environment.

## Communication

Traditional UHF/VHF radio has been used extensively for voice communication in underground mines for many years. But this communication method lacks adaptability and functionality. A wireless local area network (WLAN) is a much better solution. Indeed, several mining companies (eg, Swe-

> As ores and other desirable deposits become more troublesome to extract, increased automation and data integration become essential to successful mining operations.

**Title picture**
Although much has changed in the mining world, more automation and data integration is needed.

2 Integration of operations data with the control system

Once a communication infrastructure is established underground and mobile equipment is computerized, entirely new worlds of data exchange possibilities open up.

den's LKAB and Boliden) have installed WLAN networks underground. Such networks are most commonly used for voice over IP (VoIP) telephony and data transfer, but they also enable tracking of, and communication with, mobile equipment.

## Tracking

A tracking capability allows the location of a smartphone, laptop, radio-frequency identification (RFID) tag or embedded device to be established. Tracking can be performed using any WLAN client. Usually, the location is obtained by calculating the position of the client relative to some fixed location or anchor points with known coordinates (often the WLAN access points). Then, this relative position is transformed into a global and absolute coordinate system. In general, the more numerous the anchor nodes are, the higher the localization accuracy will be.

So that functionality such as tracking will work reliably, care must be taken when planning and deploying a wireless network underground. One major challenge is the demanding radio environment found in underground mines – eg, gallery topology, variable geology, signal attenuation in rock and construction materials, wattage versus intrinsic safety, and electromagnetic interference. ABB has performed several field trials to showcase relevant technologies and has pilot installations that demonstrate tracking of mining equipment underground.

## Mobile equipment integration

Once a communication infrastructure has been established underground and the mobile equipment fleet has been computerized, entirely new worlds of data exchange possibilities open up. For example, drill plans and loading sequences for the production machines can be delivered to them and the results of their actions reported back online. The integration of mobile equipment into the production control system has other uses too:

– To deliver the results of the initial steps of the mining process (geology, ore calculations, mine survey, mine design and production planning) to the mobile equipment systems in a useful format.
– To retrieve the results reported by the mobile equipment, such as online production status and production reports, analyses and statistics, and relay them to the relevant users.
– To retrieve execution statistics and maintenance data from onboard systems. Some of this information is used by the process control system and some (mainly the maintenance data) will be transferred to, or collected by, other entities, such as the maintenance system.
– To monitor the online status of mobile equipment, including localization information.

The interfaces to the production control system are based on industry standards. The interface between mobile machines and the open ABB process control system is OPC, specifically OPC Data Access (OPC DA), which deals with real-time data, OPC Alarms and Events (OPC AE) and OPC Historical Data Access (OPC HDA).

Data sets and naming of items conform to IREDES, the international rock excavation data exchange standard. This governs data exchange between mining equipment and office computer systems and defines

### 3 Collaboration with Atlas Copco

ABB's cooperation with Atlas Copco is an excellent opportunity for both companies. As each partner will focus on its core competencies, the joint development will create a lot of added value for underground mines.

"Our future mine operators want a compelling, all-in-one information center to optimize the utilization of our machines underground. I am sure this project will take a big leap forward in optimization of underground mining."

**David Shellhammer**
President at Atlas Copco
Underground Rock Excavation

Several mining companies have installed WLAN networks underground for VoIP telephony and data transfer, but they also enable tracking of and communication with, mobile equipment.

one common electronic language for mine automation systems.

## Mine online: mobile integration

The location information and other data from mobile equipment are obtained via the WLAN infrastructure. After consolidation, they can be viewed in the open ABB process control system. This combined information provides the basis of an accurate and online representation of ongoing activities and mining progress. Output of this analysis helps provide further optimization in different areas:

– Instead of following a predetermined routine, the ventilation control will behave to accommodate actual conditions and needs as deduced from the mobile equipment status.
– The mobile equipment availability will be improved as the asset monitors combine data from the machines and from the process environment to accurately schedule maintenance.
– The way the mobile equipment adheres to the activity planning can be monitored online and deviances used as input when recalculating the activities.

The solution will offer future mine operators unrivalled process control opportunities and information.

In the future, the control loop could be closed to automatically redirect or re-plan mobile equipment, when needed. Already, the mere fact that information regarding the surroundings (traffic situation, status of production equipment, etc.) can be compiled and made available to mobile machine operators will increase their ability to make intelligent decisions when plans and reality diverge, as they often do in the mine environment.

## Pilot installation

ABB and Atlas Copco Underground Rock Excavation, Sweden (Atlas Copco) have developed an innovative mobile integration system involving ABB's System 800xA automation platform and Atlas Copco mining machines. A successful pilot installation was demonstrated in June 2012. The solution is currently installed at the Atlas Copco test mine in Kvarntorp, Sweden → 3. This technology will offer mine operators unrivalled process control opportunities and information.

The project integrates important data from Atlas Copco underground drill rigs, loaders and trucks into ABB's System 800xA platform for better visualization and utilization of the machine fleet. By tracking locations of machines, their status and actual operating conditions underground, this solution will provide the information needed to help mine operators make the right decisions at the right time and keep production running as smoothly as possible. In line with customer requirements and future mining demands, Atlas Copco and ABB will continue to develop and add more functionality to this concept.

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# OCTOPUS-Onboard

## ABB's motion-monitoring, response-prediction and heavy-weather decision-support system

**LEON ADEGEEST – Today, industries such as offshore oil and gas are deploying larger and heavier floating production units to their fields, requiring heavy lifting capacity. Consequently, oversized cargo weighing thousands of tons is often transported via heavy-lift vessels over vast distances, demanding state-of-the-art motion monitoring, response prediction, heavy-weather decision support and weather window evaluation systems to protect their valuable cargo. ABB's monitoring and forecasting system, OCTOPUS-Onboard, has been installed on the largest and most advanced heavy-lift vessel built to date – the Dockwise Vanguard.**

1 The Dockwise Vanguard has the ability to deliver outsize cargo such as drilling rigs or offsize platforms.

With a carrying capacity of 117,000 metric tons, a length of 275 m and a beam of 70 m, the Dockwise Vanguard's ability to safely deliver outsize, very heavy cargo such as drilling rigs or offshore platforms, is unique in the specialized field of heavy marine transport → 1. Vessels such as this one enable transport of complete, assembled structures, reducing commissioning time, and also provide dry-dock capability for other large vessels such as drillships at sea.

The modular OCTOPUS-Onboard system developed by Amarcon, a member of the ABB Group, provides motion monitoring, response prediction and heavy-weather decision support aboard the Dockwise Vanguard. ABB's three-sensor motion measurement system has also been installed, so critical areas like cargo can be displayed on and monitored from the bridge of the vessel. OCTOPUS systems improve the safety and efficiency of ships, significantly reducing costs for customers. They are part of ABB's Vessel Information and Control (VICO) systems suite, which provides a full range of automation and advisory solutions specifically for marine applications, based on ABB's field-proven process automation technologies.

OCTOPUS systems improve the safety and efficiency of ships, significantly reducing costs for customers.

Installed on about 200 vessels, OCTOPUS systems deliver practical information for making decisions at sea by continually monitoring, measuring and providing recommendations about a vessel's motion, status and location, fuel use and performance, ship hydrodynamics and positioning.

The system makes use of crucial weather information and forecasts, maximizing efficient ship operations and helping the ship's crew make the best possible decisions as they deliver and deploy their cargo. OCTOPUS is part of ABB's Smart Marine initiative, which provides a range of solutions for the industry based on its expertise in marine propulsion and electrical, automation and advisory systems.

The modular OCTOPUS-Onboard system provides motion monitoring, response prediction and heavy-weather decision support.

**Title picture**
The Dockwise Vanguard, installed with ABB's OCTOPUS-Onboard monitoring and forecasting system

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# Control room convergence

## Merging industrial monitoring and control systems with data center operations

MARINA THIRY, ERIC OLSON, BOB FESMIRE – Few industrial sectors have grown as rapidly as the data center business. From mere “computer rooms” 20 years ago, data centers have become sophisticated, highly specialized, standalone installations. This growth is driven by society’s seemingly inexhaustible desire to produce data and has led to data centers becoming major consumers of power. New, showcase data centers are highly engineered and designed to be energy efficient, but for every one of these there are hundreds of average data centers that face challenges – sometimes across multiple sites. Often, the tools being used to manage these facilities are not up to the demands being placed on them. There is a universally recognized need for a unified monitoring and management system for data centers. Decathlon, ABB’s data center infrastructure management solution, is just such a system.

The growth in the size, number and sophistication of data centers over the past two decades has been staggering and there is now a robust industry dedicated to serving this sector.

Twenty years ago, data centers were known simply as "computer rooms." The growth in the size, number and sophistication of data centers over the past two decades has been staggering and there is now a robust industry dedicated to serving this sector ➔ 1. Much attention has been given to top-tier players such as Google, Apple and Facebook who invest hundreds of millions of dollars in purpose-built, highly engineered facilities. But for every one of these flagship installations there are hundreds, if not thousands, of average data centers that face difficult challenges, such as the need to reduce operating costs, manage an ever-expanding inventory of equipment and monitor multisite operations.

**Title picture**

Many data centers employ state-of-the-art data storage technology but are let down badly by their management and monitoring systems. How is ABB's Decathalon ABB's data center infrastructure management solution solving this?

## Evolution of the data center

In the early days of the Internet, data centers had little or no unified monitoring capability. There was no way to know how much energy was being used by the facility, much less by a given piece of equipment. Server utilization rates were equally unknown. In fact, there was no pressing need to know – energy was cheap and capacity was not an issue.

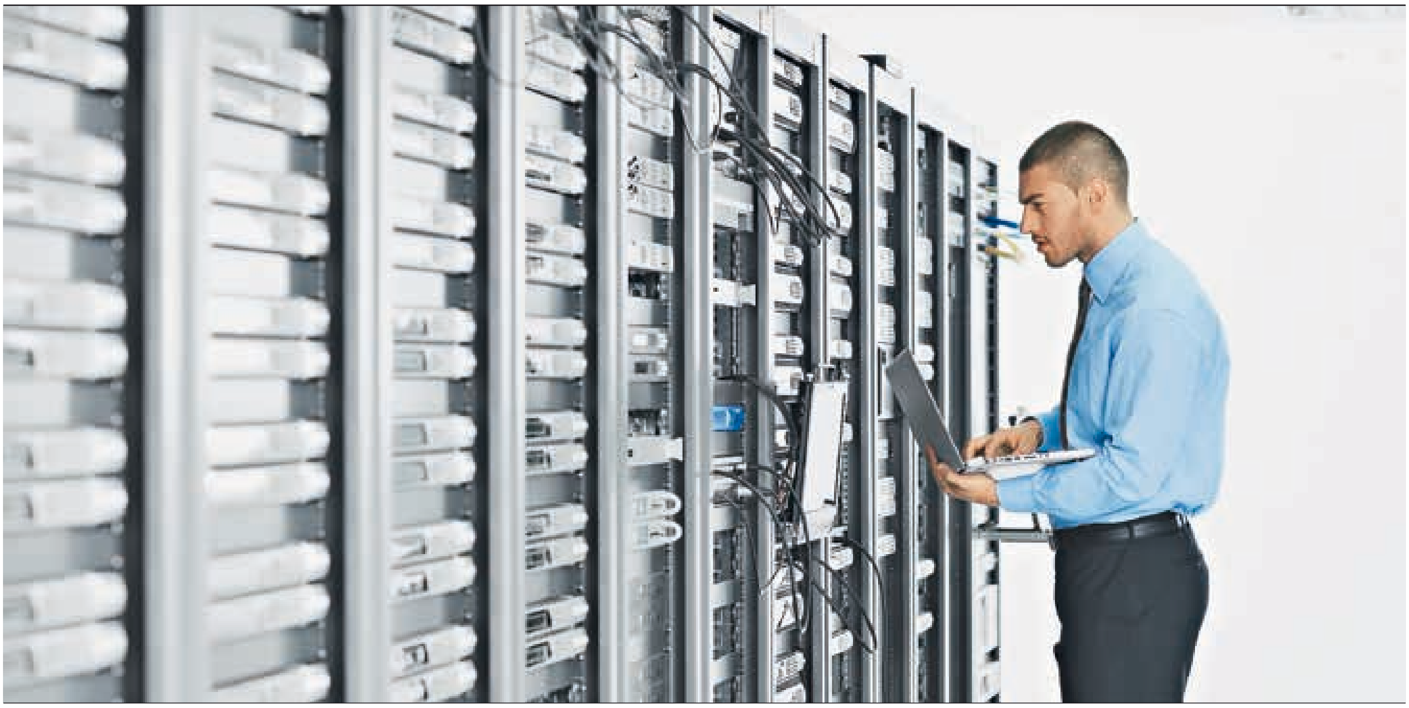
The surge in IT and the growth of the Web has caused an exponential rise in data storage and a similar rise in energy consumption: Just five years ago, typical servers drew around 2.5 kW per rack, but today, servers consume between 8 kW and 30 kW per rack – posing a huge cooling challenge.

In response, many data centers have implemented hot aisle/cold aisle schemes, for example. These manage air flow to avoid hot and cold air mixing. However, this type of solution is passive. When it comes to active monitoring and control, the systems in place today are often inadequate. Point solutions are available, for example to manage server virtualization or monitor energy use on a facility-wide basis, but, importantly, these systems are not integrated, thus adding complexity and introducing information gaps.

In other areas, data centers still lag other industries by a wide margin. Asset management, for example, is generally understood to mean the systematic monitoring of equipment status and performance in order to better manage maintenance and optimize the operations and maintenance budget across the entire equipment fleet. In the data center world, asset management has historically meant simply keeping track of the purchase date and physical location of equipment.

ABB estimates that only around 5 to 10 percent of data centers have monitoring and control systems in place for server operations, energy consumption and environmental control. Another 20 to 40 percent have some monitoring and con-

1 Few data centers monitor and control energy consumption.



DCIM systems must be highly reliable and also offer asset management capabilities that go well beyond simply keeping track of servers.

trol capability — usually around server operations – and the remaining 40 to 65 percent have little or none. This is because many older facilities were treated as just another commercial office space, albeit with some unusual electricity requirements, and had to make do with the already-installed conventional building management systems to control temperature and humidity.

### Enter data center infrastructure management

There is, then, a need for a unified monitoring and management system for data centers. It should have a single user interface that reduces the complexity of burgeoning point solution interfaces. It should also manage server operations as well as cooling, environmental controls and energy use. The good news is that process industries have already tackled many of the same issues, so the data center industry is in a position to leverage those mission-critical systems in building its own. This field of technology development has been labeled data center infrastructure management (DCIM).

From a strategic standpoint, DCIM is about aligning the data center with business goals and realizing greater value from it through:

- energy and performance information
- operational decisions supporting business initiatives
- delivery of new apps and web services in the most reliable and efficient way possible.

### DCIM characteristics

Several characteristics are essential in a DCIM. Uptime is the most critical parameter for the data center industry, so DCIM systems must be highly reliable. DCIM systems must also offer asset management capabilities that go well beyond simply keeping track of servers: Condition-based maintenance and diagnostic tools (eg, to identify servers running in a loop) will bring asset management in the industry into line with other equipment-intensive businesses. As more and more operators manage multiple data centers, computer rooms and server closets, multisite visibility becomes another must-have for DCIM.

Ultimately, DCIM provides the visibility, decision support and control technologies to better manage data center operations, enterprise-wide, through a unified view that spans mechanical, electrical and IT systems. DCIM systems promise to deliver actionable information to data center operators so they can maximize capacity, optimize their operations and reduce cost and risk. Decathlon, ABB's DCIM solution, takes up this challenge and offers a significant improvement over the status quo:

Data centers will instantly shift "production" from one location to another to exploit differences in energy prices.

**Facility management**
Monitoring and control over facility systems, such as air conditioning, air handling and mechanical and electrical equipment.

**Maintenance management**
Shifting from time-based to condition-based maintenance using automated prognostics and diagnostics to identify and resolve issues before they become problems.

**Power management**
Monitoring and control of devices, power systems and meters, including the substation, microgrid and on-site power generation, to ensure safe and reliable power distribution and consumption.

**Energy management**
Combining real-time energy consumption data with energy contract information, real-time pricing and demand response for energy cost optimization.

**Resource forecasting and energy planning**
Services from third parties provide additional value by optimizing the energy value chain and allowing participation in energy markets. For example, a data center service called Global Energy Intelligence® by Power Assure is a subscription service embedded in Decathlon that delivers server metrics, IT analytics and forecasting, worldwide energy market integration, demand response, ancillary services, energy pricing and forecasts.

**Asset and capacity planning**
Nlyte Software's DCIM suite has been embedded in Decathlon. It can optimize space, power and cooling capacity through intelligent placement of IT assets. It also models what-if scenarios and automates and manages workflow processes.

**Troubleshooting**
Root-cause analysis and alarm management – providing granular performance detail for the entire data center operation.

**Control and automation**
Enabling facility and IT performance optimization at a device and system level.

**Remote monitoring**
Real-time monitoring of all assets and environmental conditions.

## The case for DCIM

The need for visibility, decision support and control technologies for rapid response in data centers is clear and DCIM offers a solution to the patchwork of point solutions that many facilities rely on today. DCIM is still new, but a few overarching concepts have emerged that are likely to guide the development of these systems:

**Visibility and better control**
The essence of the DCIM business case is to establish a realistic baseline of data center energy use through real-time, comprehensive monitoring, so operators know when, where and at what rate energy is being consumed. Armed with that information, they can then take tactical measures to optimize resources and forecast energy requirements.

**Resource consolidation**
DCIM systems leverage increased visibility along with powerful analytics to consolidate resources and eliminate waste, thus maximizing existing capacity. This leads to hardware savings (eg, fewer servers), data center savings (eg, power, cooling and space) and reduced environmental impact.

**Performance optimization**
DCIM uncovers the true state of data center operations with better visibility and control to improve availability; maximize capacity of power, cooling and space; streamline operations; and reduce risk across the enterprise.

**Facility and IT automation**
DCIM systems can assist with tasks like load shifting and temperature and humidity control, as well as tracking other parameters, such as vibration in HVAC units, so as to pre-empt failures.

## What comes next?

For the vast majority of facilities that do not enjoy the advantages of cutting-edge systems and design, a step-wise approach to improving data center operations is advisable.

A site evaluation is always a good first step as it reveals where the most immediate gains can be made (eg, in energy savings). Also, the eventual introduction of a DCIM system is made easier if the operators know what they want from it.

Retrofits should begin with simple initiatives with quick payback (ie, less than one year). These might include increasing room temperature or installing variable speed fans in the cooling system.

One example of where DCIM is headed lies in the potential for data centers to shift workload from one location to another to exploit differences in energy prices. This instant shifting of "production" is something of which "old economy" businesses can only dream. Ideas such as these will drive further refinement of DCIM systems and will play a central role in such products realizing their full potential and becoming an integral part of every data center in the industry.

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**Reference**
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# Virtually speaking

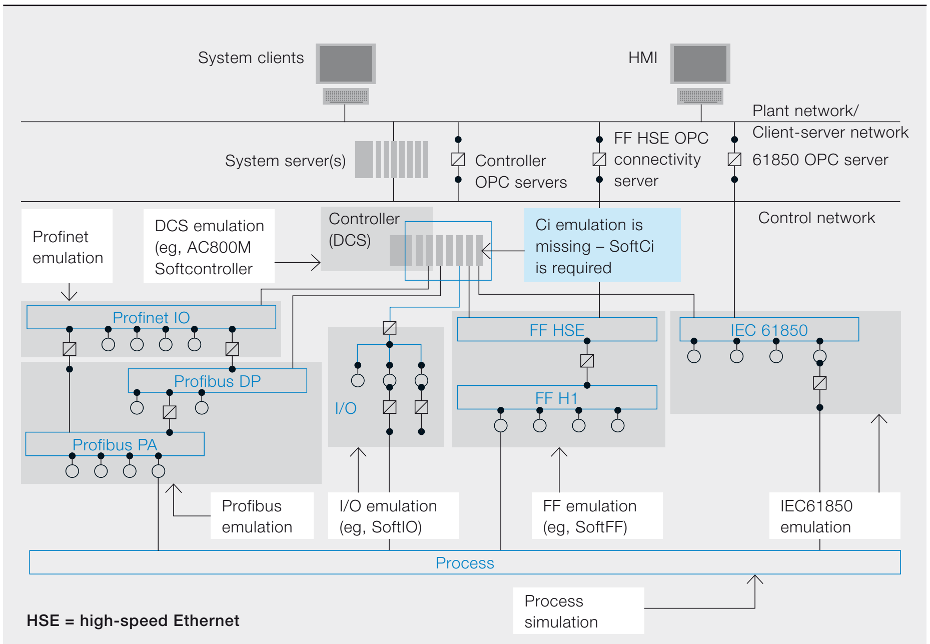
## DCS-to-subsystem interface emulation using SoftCI

MARIO HOERNICKE, TRYGVE HARVEI – A modern industrial plant is a thing of bewildering sophistication. Hundreds, or even thousands, of sensors, meters and various intelligent field devices send data to, and receive data from, automation controllers in a vast, precisely orchestrated torrent of bytes. Building a full hardware test infrastructure in the factory for such a complex system is wholly infeasible, so software emulators are used to imitate its constituent subsystems. Over the years, these have become very refined. However, missing from such emulation environments has been a satisfactory way to emulate the interfaces between the subsystems and the distributed control systems they serve. A research initiative launched to solve this problem resulted in SoftCI. SoftCI is meant to replace AC800M controller communication interfaces during integration and factory acceptance tests.

**Title picture**
Emulating the control environment of a complex industrial plant, such as this liquified natural gas plant in Norway, in software and hardware is a difficult job. A new emulator that ably imitates subsystem interfaces is now making the job a lot easier.

Today, each system has to be tested separately in its own context without regard for system or communication aspects.

1 Emulators for process control system hardware – situation today. SoftCI is needed for communication between the components.




Obviously, a complete process plant cannot be built in the lab to test new automation systems. So, the plant's functions are emulated in hardware and software. Whereas much of the plant's functionality can now be successfully imitated, the communication between the distributed control system (DCS) emulator and subsystem emulator is usually not. Due to the increasing usage of fieldbuses and Ethernet in plants, and the criticality of error-free communication, this is a major problem

Since the communication functions of different CIs are often similar, one generic communications concept could cover many CI types.

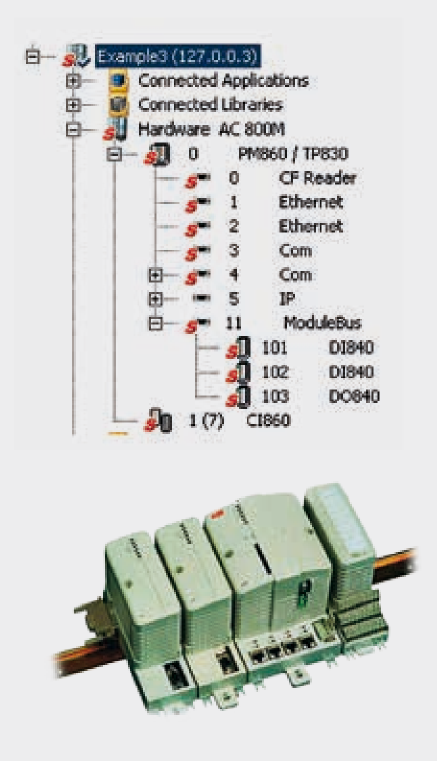
The Next Generation Factory Acceptance Test (NGFAT) initiative aims to solve this problem [1]. Included in the goals of the initiative is the development of a generic controller communication interface (CI) emulation – SoftCI. As a result, a software development kit (SDK) has been implemented that allows the user to integrate CI emulation into existing subsystem emulators or execute it in standalone mode. SoftFF [2], a Foundation Fieldbus simulator, can be used to verify the integrity of the emulation.

## SoftCI environment

During an FAT, the entire system must be comprehensively emulated in order to test the consistency of the engineering effort. Everything that is not performed on a standard PC is executed on an emulator. Different emulators represent different subsystems and fieldbuses → 1. There is, for instance, a DCS/controller emulation available that focuses on IEC61131-3 code [3]. Today, each system has to be tested separately in its own context without regard for system or communication aspects.

It is against this background that SoftCI was developed. SoftCI handles vertical communication between the DCS and subsystem emulations. A plant will have many subsystems performing many different tasks, but usually only one DCS type. In order to show that the SoftCI concept works, attention has been focused on the ABB AC800M controller.

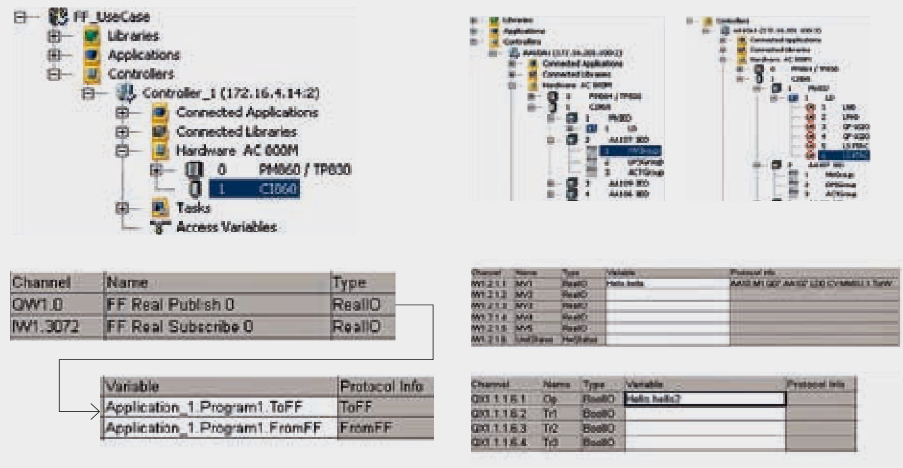
2 Topology of AC800M. Here, the usage of an FF coupler.




3 Characteristics of Foundation Fieldbus CI860 and IEC61850 CI868, showing the mapping done inside the CIs in Control Builder M (CBM).

Foundation Fieldbus (CI860)

IEC61850 (CI868)




Characteristics

| Foundation Fieldbus (CI860) | IEC61850 (CI868) |
|---|---|
| – One CI for input and output variables<br>– FF Signals are copied to 1131 variables (and vice versa)<br>– Mapping is configured in a single table for each CI | – One CI for input and output variables<br>– IEC61850 signals are copied to 1131 variables (and vice versa)<br>– For each IED, a separate mapping table is engineered<br>– IEDs from the field are always inputs<br>– AC800M is treated as being an IED<br>– AC800M IED is always an output |

## In focus: AC800M

The AC800M controller contains input and output (I/O) modules, but also fieldbus and subsystem couplers – the CIs. A coupler is a specific component used to connect the physical fieldbus on the device level → 2.

A CI860, for instance, transfers data between the AC800M and a Foundation Fieldbus (FF) device. It is engineered using a table to map IEC61131 control application variables to FF signals. While IEC61131 variables are connected to the control application, FF provides the counterpart within the corresponding engineering tool, FieldBus Builder FF (FBB FF). The FF signals are attached to the FF function blocks using FBB FF. By connecting the signal to the function blocks, the IEC61131 variable to the control application and mapping the signal and the variable in the mapping table, the engineer can establish a value exchange between AC800M and FF.

Another example of a CI is the CI868 for IEC61850 [4] networks. For IEC61850 the structure below the CI looks different. The CI contains a separate mapping table for each intelligent electronic device (IED) that is attached to the controller. In this table, the signals coming from the subsystem can be mapped to the control variables, as for FF.

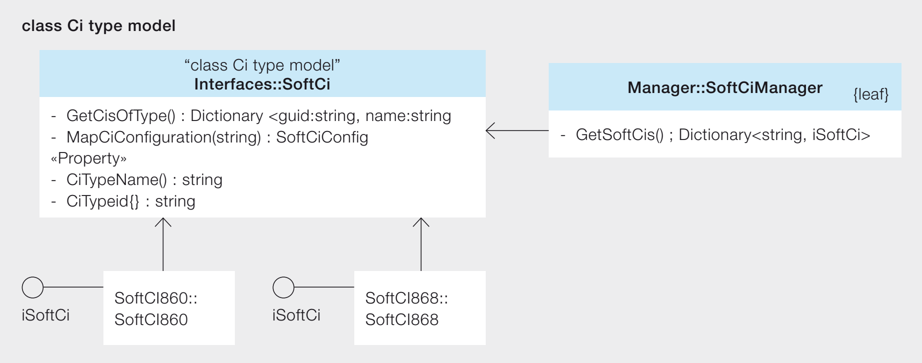
Except for the difference that FF uses a single table and IEC61850 uses several, the CI scheme is similar → 3.

Since the communication functions of different CIs are often similar, one generic communications concept could cover many CI types. For example, most CIs are used to simply exchange values from IEC61131 variables to subsystem signals and do not provide supplemental functionality. Thus, a configured CI could be modeled as a mapping table.

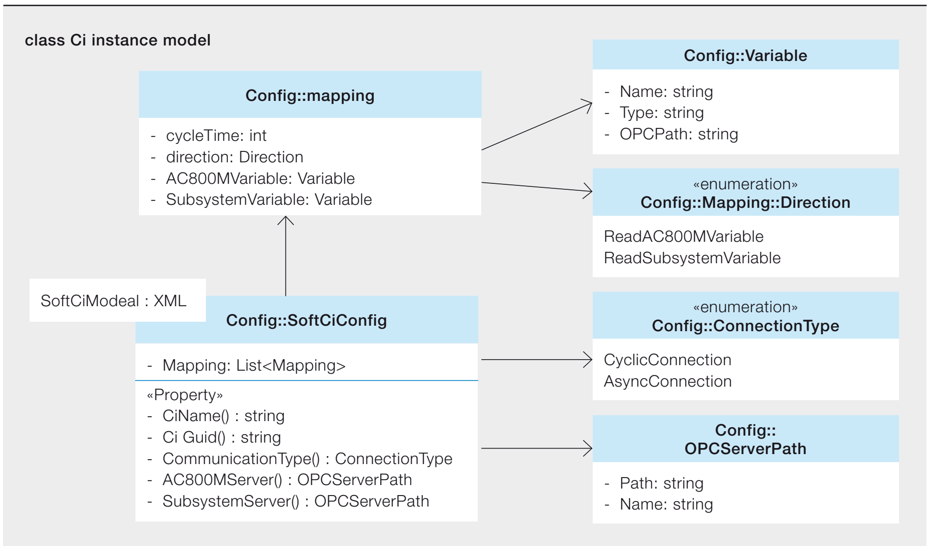
The model of the CI is not the only part that needs to be developed. During runtime, a generic communication method has to exchange values with the AC800M. This is required for every type of CI since the CIs are always exchanging data with the AC800M. On the field level, so to speak, a communication to the subsystem emulator is required. The subsystem emulation differs depending on the subsystem type. The emulation can be ABB-owned, open-source or third party and can be characterized as being either open or locked.

# SoftCI handles vertical communication between the DCS and subsystem emulations.

**4 CI model for a specific type**




**5 CI model of a specific instance**




Open emulators allow further functionality to be included: The SoftCI could be integrated into the subsystem emulator and directly exchange the variables from the AC800M with the subsystem emulator's variables. The CI model is executed within the subsystem emulation.

Locked emulators do not allow expanded functionality. These tools, however, should still be usable with SoftCI and, therefore, a different vertical standard communication method needs to be evaluated. This implies that SoftCI should be able to execute CI models in standalone mode and that a CI model might be developed manually and must, therefore, be stored in a human-interpretable form.

## Generic CI emulation

The scene has been set, then, for the development of generic functionality to emulate different CI types.

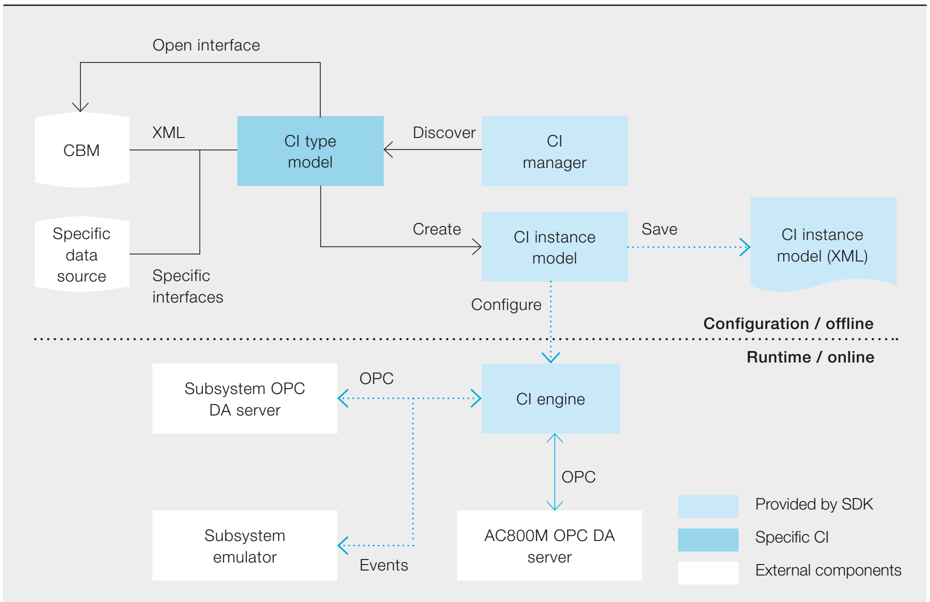
## CI models

A major part of the functionality is the creation of CI models. CI models consist of one part that describes the CI type and another part that describes the CI instance. The model for the CI type is developed once and is the same for each instance, while the instance model is created for every instance separately.

The meta-model for a CI type is delivered as a .NET interface that can be implemented in a class ➔ 4. It consists mainly of the descriptive properties, name and ID of the CI type, and a method to get the instances of the described type from the 800xA engineering workplace. If automatic creation of instance models is desired, a method to create the model can be implemented. If this is done, SoftCI can identify the instances and create the models for the instances without user interaction.

The meta-model for the instances is delivered as .NET classes, but is storable as XML ➔ 5. The instance meta-model does not use methods, but data properties only to describe the specific instance. In general, it is the representation of the mapping table from CBM.

6 SoftCI SDK modules




A CI860, for instance, transfers data between the AC800M and a Foundation Fieldbus device.

In addition to the mapping table from CBM, the name and ID of the CI instance is described. With those, SoftCI can show the user which instances are emulated at present. Additionally, the communication type of the CI instance needs to be described. The communication type might by acyclic or cyclic, depending on the communication method of the subsystem. Mixtures of both are allowed.

## CI communication

As mentioned above, a method to communicate with the AC800M Softcontroller had to be found, so the communication parameters for an instance have to be modeled.

The chosen communication method is OPC Data Access (DA). OPC DA is supported by the AC800M Softcontroller and is usually preconfigured for the actual hardware and the production system. Hence, reconfiguration for the emulation is not required. Since there might be several OPC servers used in the process control system, the path to, and name of, the AC800M OPC server for the specific controller instance has to be described within the instance model.

## SoftCI modules

The SoftCI SDK consists of a number of software modules → 6. Besides the model, a CI manager is supplied that can be used to identify CI type models. It is possible that several types are used within a single process control system for a plant. The manager can identify them and automatically create instance models for each without user interaction.

The modules delivered with the SDK are provided as class libraries that can be used to quickly create CI emulation within subsystem emulators. Additionally, a very small and simple user interface is provided that can be used to execute CI emulation in standalone mode.

## Testing times

The concept described has been successfully tested by implementing CI emulation for FF. The concept has been proven in conjunction with IEC 61850 emulation too. SoftCI868 has been implemented in prototype form and value exchange between IEC 61850 emulation and the AC800M softcontroller functions.

## Towards the virtual plant

SoftCI is an SDK that provides generic emulation functionality for AC800M communication interfaces and, in doing so, closes a white spot in the emulator landscape. Although it might not be usable for every kind of CI, the majority of CI types can be addressed. SoftCI860 has already been im-plemented in SoftFF and is ready for use in integration testing and FATs (a first pilot project is currently underway).

SoftCI is an evolutionary step towards exhaustive virtual commissioning functionality for ABB's Extended Automation System 800xA – ie, another important step towards perfection of the virtual plant.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[3] IEC61131-3: *Programmable controllers – Part 3: Programming languages.* Edition 2.0, 2003.

[4] IEC61850: *Communication networks and systems in substations, 2003.*

# CRIM

## Identifying the best maintenance strategy for complex process plants

KARI SAARINEN, SHIVA SANDER TAVALLAEY, PATRIK M. WESTERLUND
– Changing from a reactive to a preventive maintenance strategy can yield substantial cost savings in many sectors of industry. However, in the process industries, an installation may have many thousands of maintenance-worthy elements, rendering a solely preventive maintenance strategy impractical or even impossible. How then to determine the optimal maintenance strategy mix for such situations? CRIticality-analysis-based Maintenance (CRIM) optimization introduces a systematic maintenance planning methodology for identifying critical equipment and appropriate preventive maintenance plans, taking into account environmental and process conditions. The method utilizes fast criticality assessment of the plant equipment prior to life-cycle cost analysis.


CRIM can deliver a cost-effective maintenance strategy for the whole plant by systematically utilizing criticality analysis, life-cycle cost analysis and lifetime estimates.

The term "maintenance optimization" touches on a wide range of approaches from simple experience-based, rule-of-thumb methods to complex systematic methods. Examples of simple methods include run-to-failure maintenance, appropriate for redundant equipment and equipment with very low failure rate; time-based maintenance (TBM), most effective when the regular overhaul/replacement of the equipment is cheap compared with the cost of a failure and a single, known failure mode dominates; and condition-based maintenance (CBM), which is most cost efficient for critical equipment.

The more complex approaches include reliability centered maintenance (RCM), the most thorough method to determine the right proactive maintenance approach to use for high system reliability, and total productive maintenance (TPM), which combines total quality management and proactive maintenance policies in order to achieve maximum production efficiency. RCM is a rather weighty approach and TPM focuses on maximizing machine throughput, so neither is appropriate in the context discussed here. However, ABB's CRIM methodology does fit the bill as it can deliver a cost-effective maintenance strategy for the whole plant by systematically utilizing criticality analysis (CA), life-cycle cost analysis (LCCA) and lifetime estimates.

Criticality factors are reached by consensus with the maintenance and process experts.

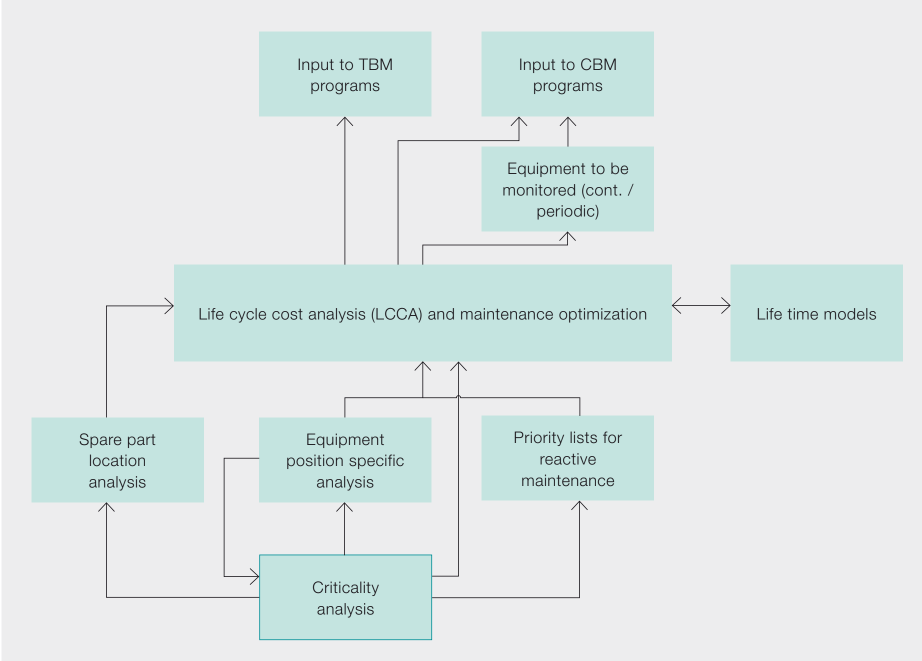
**Title picture**
Deciding on appropriate maintenance strategies in a plant with many thousands of devices (like this iron ore pelletizing facility) can be tricky. CRIM helps identify appropriate maintenance plans.

## CRIM

The CRIM process starts with a criticality analysis – a key process in any main-

Criticality assessment includes the quantitative analysis of events and faults and the process of ranking them in order of the seriousness of the consequences.

1 CRIM process flowchart




tenance and reliability method → 1. CA provides the basis for determining the value of specific equipment and the impact it has on the safety of people, the environment and the production process. CA also determines the level of attention that equipment requires in terms of maintenance strategy and tactics.

In the CA team meeting the facilitator asks a set of carefully selected questions and chooses the criticality levels for each criticality factor.

The second step in the CRIM process is the LCCA, which is performed for critical objects to show the benefits of using certain maintenance programs for that object → 1.

### Criticality analysis

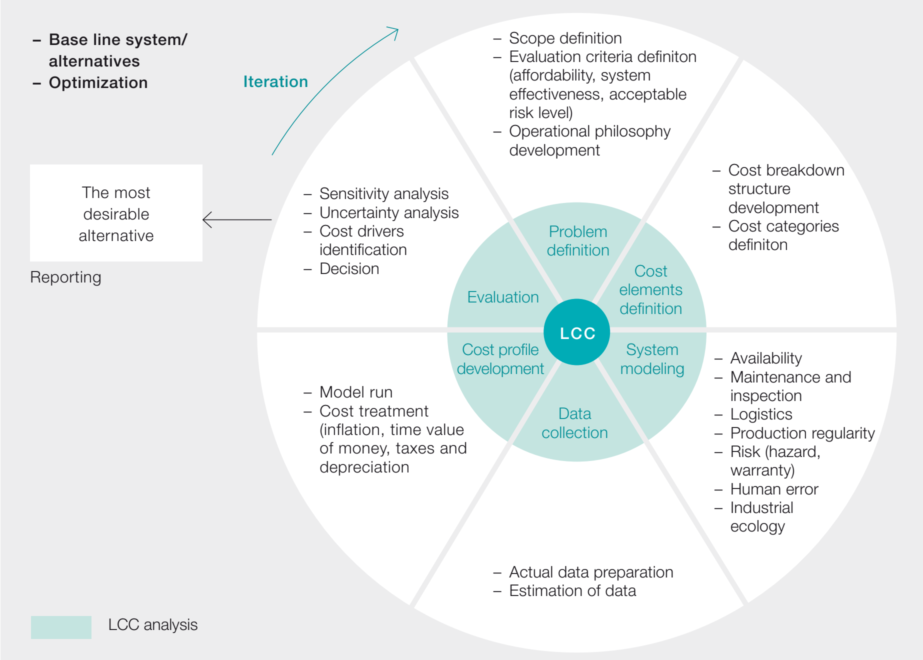
Criticality is a relative measure of the consequences of a failure. Correspondingly, a criticality assessment includes the quantitative analysis of events and faults and the ranking of these in order of the seriousness of the fault consequences. In other words, only the consequences of failures are assessed in this approach; probabilities of failure are considered later in the LCCA.

With a well-defined process and proper tools, it is possible to cost-effectively assess thousands of pieces of equipment.

Prior to starting the criticality analysis, ABB's facilitator asks the customer to load a list of all the equipment positions to be analyzed into the CA tool. In the CA team meeting, the facilitator asks a set of carefully selected questions for each position and, from the answers, chooses the properly calibrated criticality levels for each of the tabulated criticality factors. These factors will have been previously identified in discussions with the maintenance and process experts. The final criticality level that is automatically generated for each asset takes downtime, production response time, capacity, quality, environment, safety and energy losses caused by equipment failure and eventual secondary effects all into account. From all this, a CA report is generated.

### Life-cycle cost analysis

LCCA is a collective activity comprising many kinds of analysis aimed at calculating the costs and profitability of a system or piece of equipment over its life span, including research and development, 2 An LCC concept map [1]




The difference between production losses due to equipment failure and those due to preventive maintenance action is the key element in the analysis.

LCCA is a collective activity comprising many kinds of analysis aimed at calculating the costs and profitability of a system or piece of equipment over its life span.

construction, operation, maintenance and disposal → 2. LCCA starts with the problem definition process as shown in the figure and proceeds clockwise in an iterative fashion until all the criteria defined in the first process are satisfied.

In the CRIM case, the problem is to determine the minimum long-term average maintenance costs per unit time calculated for reactive, time-based and condition-based maintenance strategies.

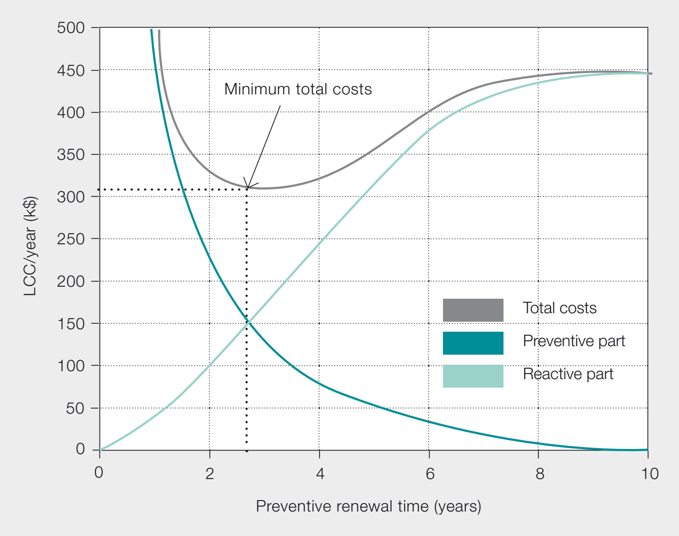
The LCCA concept applied here only considers those costs that depend on the selected maintenance strategy for that piece of equipment. Thus, the only capital cost considered is the specific equipment cost required for CBM. Accordingly, there is no capital cost related to the reactive maintenance strategy. Operational cost is divided between fixed annual cost and costs due to reactive or preventive maintenance actions. The fixed annual cost includes only costs due to condition monitoring.

The difference between production losses due to equipment failure and those due to preventive maintenance action is the key element in the analysis.

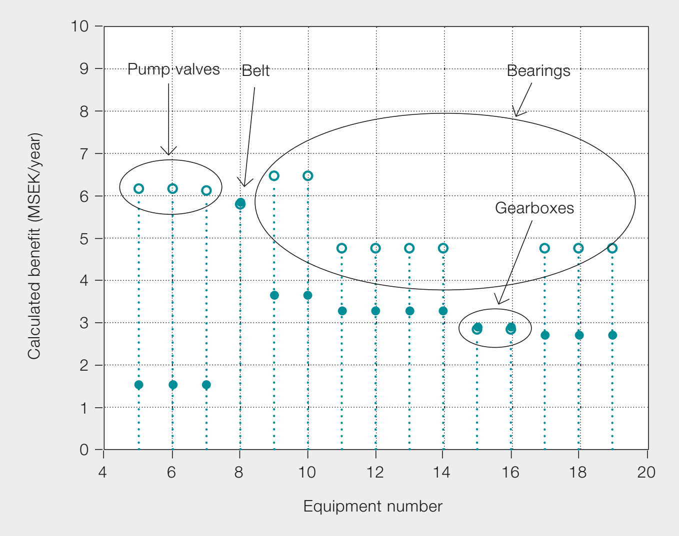
Proactive or preventive maintenance is initiated based on predictions of maintenance need and its definition does not include the diagnostics stage. If the process is well-designed and preplanned, the production downtime should be much shorter than in the reactive process. Also, any necessary materials can be ordered before the failure occurs so that they are ready for use when needed.

Thus, the average maintenance cost during a period is a sum of different maintenance costs, each weighted by the frequency of the particular maintenance type. The frequencies and the total number of maintenance actions depend on the selected maintenance strategy. These frequencies are estimated by lifetime models that incorporate the operational conditions of the maintenance objects. These conditions – temperature, dirtiness, loading, etc. – are assessed

3 LCC of a maintenance object renewed after a certain number of years or at failure




4 Benefit of using TBM (full circles) or condition monitoring (empty circles) calculated for the equipment with process criticality 4 or 5




In the CRIM case, the problem is to determine the minimum long-term average maintenance costs per unit time calculated for reactive, time-based and condition-based maintenance strategies.

during the position -specific analysis of the critical equipment described above.

The next step in the analysis is to use the lifetime and cost models to formulate the life-cycle cost (LCC) model for each of the maintenance strategies. In one real-life TBM example, where the component is replaced after it reaches its planned preventive replacement age or at failure time, whichever comes first, the optimum replacement time is found to be 2.8 years, which gives an LCC of $310,000 per year → 3.

LCCA can also be applied to optimize spare part location by calculating different LCCs for a selection of these locations.

The impact of changes in input parameters on the result can be examined by sensitivity and uncertainty analysis. Varying the input parameters over a certain range can show the impact of the major factors and tradeoffs on cost.

## CRIM figures

A two-day CA at a pilot customer site took in 698 pieces of equipment from two process lines. The calibration and introduction took about half a day. Assessment of the first 100 units took the remaining half of the first day. Afterward, the speed of assessment varied between 50 and 100 units per hour. The CA feeds the LCCA and the tool lists final costs calculated by the LCCA for identified critical components → 4.

All the LCC results calculated for one object, eg, a gearbox, can be summarized → 5. The dashed lines in the figure show the uncertainties of different LCCA estimates. In this case, there is an optimum time interval for the TBM strategy to compete with corresponding CBM strategies. On the other hand, it is shown that a TBM that does not occur during the scheduled maintenance breaks does not have any minimum and is more expensive than reactive maintenance. Sensitivity analysis is usually performed to calculate the effect on the LCC result of a small positive or negative change in every parameter value.

The spare part list generated by the CA tool is used for further optimization of spare part locations using LCCA.

5 LCCs of the “gear box 1” example as a function of replacement age. Ten percent uncertainty (dashed lines) is assumed in the lifetime model parameters.


6 The consequence of decreased criticality value on the LCC due to change of spare part location

| Group name | Criticality change | LCC change (k$/year) | Spare part cost (k$) |
|---|---|---|---|
| Switches | 5 ➔ 2 | 350 | 31 |
| Pump valves | 5 ➔ 3 | 512 | 15 |
| Cooling fans | 3 ➔ 1 | 113 | 3 |
| Sensors | 3 ➔ 1 | 77 | 3 |

A comparison of the calculated LCC for the listed objects with two different assumptions about the spare part locations – namely, logistic delays of more than one day versus one hour – shows that, in some cases, the LCC can be decreased drastically just by moving the spare part closer to the equipment, or by increasing the availability of the spare part.

Furthermore, changing the location of the spare part may directly affect the criticality value calculated in the CA tool – a decrease from the highest value of five to the noncritical value two was observed in the example ➔ 6.

The consequences of such a decrease of criticality value can be seen in the change of LCC ➔ 6. The corresponding spare part cost used in the calculation is only a fraction of the LCC cost.

## CRIM solution

CRIM goes a long way to solve the plant owner´s conundrum of finding an optimum mixture of predictive, preventive and run-to-failure maintenance strategies for the thousands of pieces of equipment in his plant. In the pilot site, by choosing an appropriate CBM strategy and by applying good condition monitoring methods for critical pump valves and bearings, LCC savings of $620,000 per year were identified.

One main finding of the pilot study is that CRIM analysis would be appropriate during the plant design phase or as part of the factory acceptance test. Moreover, it is of vital importance that the process involves expertise from all fields.

Perhaps the strongest endorsement of the CRIM approach was the customer’s comment, “Can we afford not to do CRIM analysis for the whole plant?”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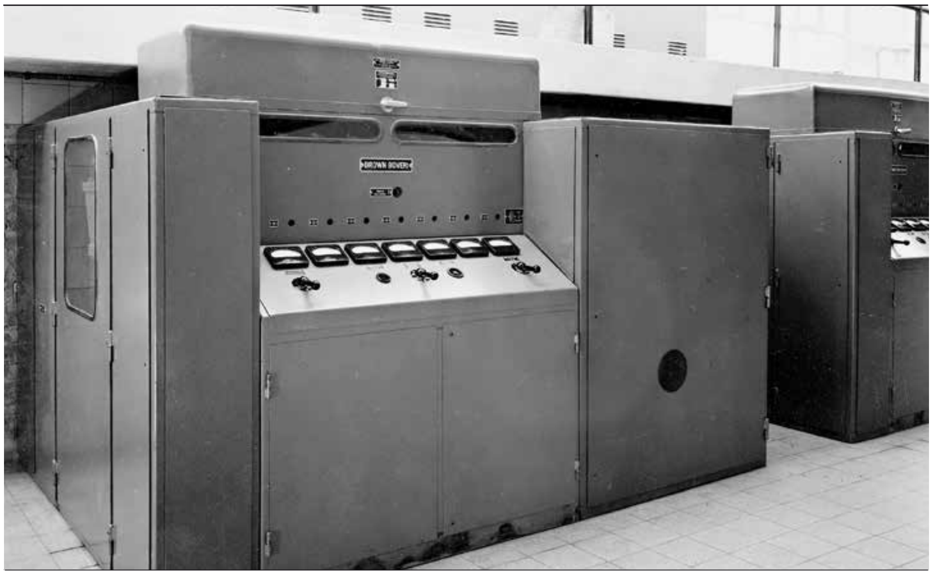
# From mercury arc to hybrid breaker

## 100 years in power electronics

ANDREAS MOGLESTUE – 2013 marks the centenary of the involvement of ABB (and its forerunner companies) in power electronics. Power electronics have become ubiquitous in a vast range of applications ranging from large HVDC (high voltage direct current) installations – transmitting gigawatts over thousands of kilometers – to everyday household devices. The development of power electronics was driven by the desire to convert electricity from one frequency or voltage level to another, without having to resort to moving (and hence maintenance-intensive) mechanical parts. In the early days, converters used mercury-arc rectifiers. These were replaced by semiconductors from the 1950s and 1960s. ABB has, throughout this 100 year timespan, been a pioneer both of the technology itself and of its applications.

1 A BBC contact converter from the 1950s (rated output 5,000 kW at 200 – 500 V)



The early years of the commercial use of electricity were marked by competition between different distribution technologies. Edison's DC vied with Tesla's AC in a battle that the latter ultimately won. Whereas many applications are well suited to AC, there are also uses for which DC remains indispensable, thus requiring a means of converting AC to DC. These applications include electrolysis (such as for the manufacture of aluminum), battery charging, wireless communications and the electrification of tramways, metros and some railways. These applications are still an important part of ABB's business today. The list has since been extended by the inclusion of newer applications such as data-centers and HVDC transmission.

From an early stage in the development of electrical systems, inventors were seeking to convert AC to DC (rectification) and DC to AC (inversion), as well as creating variable output from fixed input (eg for variable-speed drives). Most power electronic applications today can still be placed in one of these three categories.

A precursor technology for AC to DC conversion was the motor-generator (a motor and generator fixed to a common drive shaft). The principle could equally be reversed (for DC to AC conversion), or indeed used to convert between two different frequencies of AC (several European countries electrified their railways at 16⅔ Hz because this figure is precisely one third of 50 Hz). The motor-generator setup could even be expanded for variable output applications: For example the Ward-Leonard control uses the excitation of the DC generator to vary its output voltage (permitting, for example, a variable-speed drive). The Scherbius machine permits the connection of non-fully synchronized AC grids by allowing some phase slippage.

One valuable property of motor-generators is their ride-through resilience. Short power interruptions are bridged by the kinetic energy of the rotating mass. It is interesting to note that this energy-buffering functionality is mirrored by DC-link capacitors in today's power-electronic converters.

The drawbacks of mechanical converters include maintenance to moving parts, such as lubrication and changing of carbon brushes, and the significant mechanical forces affecting construction and anchoring.

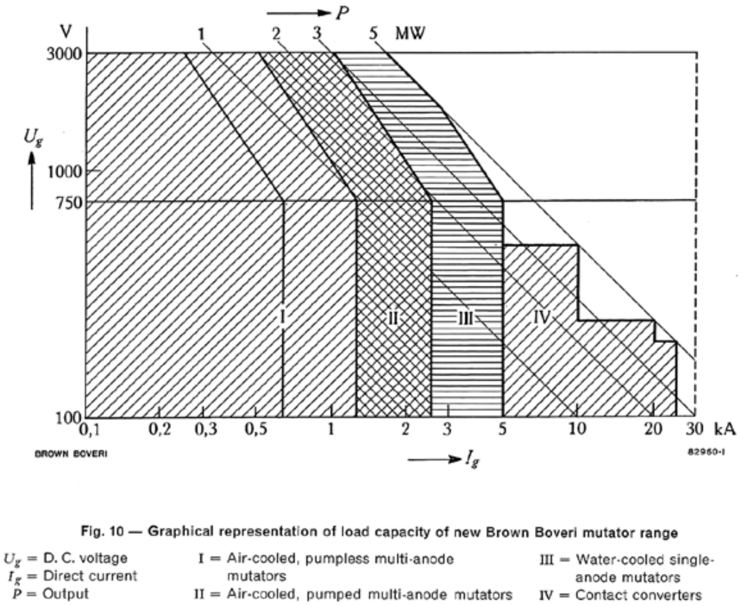
Converters relying on mechanical switches remained a maintenance liability. Power electronics set out to achieve similar results but without moving parts.

## Switching

Whereas motor-generators feature a complete galvanic separation of the input and output, power electronics achieve conversion by changing the current path at discrete moments through externally-triggered switching actions. In its simplest form, the principle of path switching can be observed in the DC motor, where a commutator reverses the flow of current in the rotor winding in function of its position (a simple DC to AC conversion). Another approach to a more general-purpose AC-conversion is the contact converter → 1. This converter features fast-moving mechanical contacts (effectively an H-bridge, but with mechanical switches rather than valves). One notable weakness was that, in contrast to motor-generators, the waveform of the AC output was not a sine wave but a rectangle. This drawback was shared with many power-electronic circuits. As will be discussed later in this article,

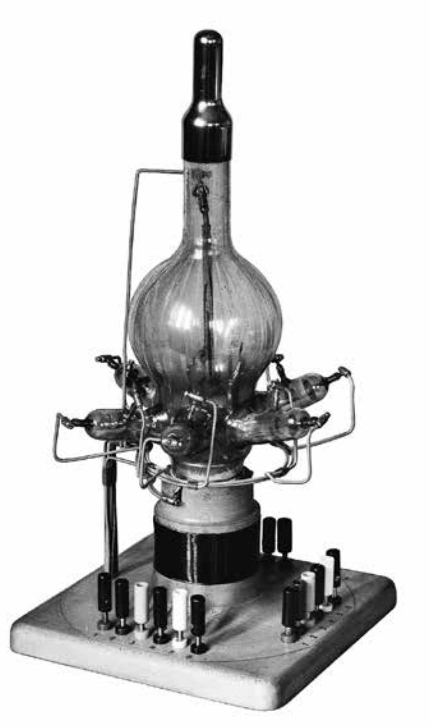
**Title picture**
A diode for traction applications (circa 1980)

2 Power ranges of different switchable BBC mutator types (and contact converters)




Source: T. Wasserrab, Mutator Meeting at Baden in 1955, Introductory Lecture (proceedings published by BBC)

3 An early mercury-arc valve enclosed in glass



ASEA built the world's first permanent and commercial HVDC link, connecting the Swedish island of Gotland to the mainland in 1954.

overcoming this was to be one of the major points of progress in the domain of modern power electronics.

Like motor-generators, converters relying on mechanical switches remained a maintenance liability. Power electronics set out to achieve similar results but without mechanical switches.

Despite their apparent drawbacks, contact converters were able to fulfill current ratings beyond the scope of mercury-arc valves → 2, and their production continued until the rise of silicon-based converters.

## Mercury-arc valves

In the early years of the 19th century, the British chemist and inventor, Humphry Davy, showed that an electric arc could be created by passing current through two touching rods and then drawing them apart. A plasma (gas of ionized particles) forms in the gap between the electrodes and conducts current. The recombination of ionized particles in the plasma causes the emission of light, whereas the heat generated by the current creates new ions (excitation) and sustains the arc. It is interesting to observe that the underlying physics of today's semiconductor switches is equally concerned with the excitation, movement and recombination of charge carriers.

In 1902, the American inventor, Peter Cooper Hewitt, demonstrated a setup with one electrode made of mercury and the other of steel (carbon in later versions), enclosed in a glass bulb containing mercury vapor. An interesting property was that current would conduct from the carbon to the mercury electrode but not vice versa. Whereas the pool of mercury readily emitted electrons once the arc was ignited, the carbon anode did not to any appreciable extent (in the operating temperature range). The mercury vapor was ionized by the arc, and the bombardment of mercury ions onto the mercury cathode generated sufficient heat to sustain its continued emission of electrons. The mercury-arc valve was born, and with it, power electronics.

In the following years, numerous inventors and companies sought to improve and commercialize this rectification principle.

## Manufacture of mercury-arc rectifiers

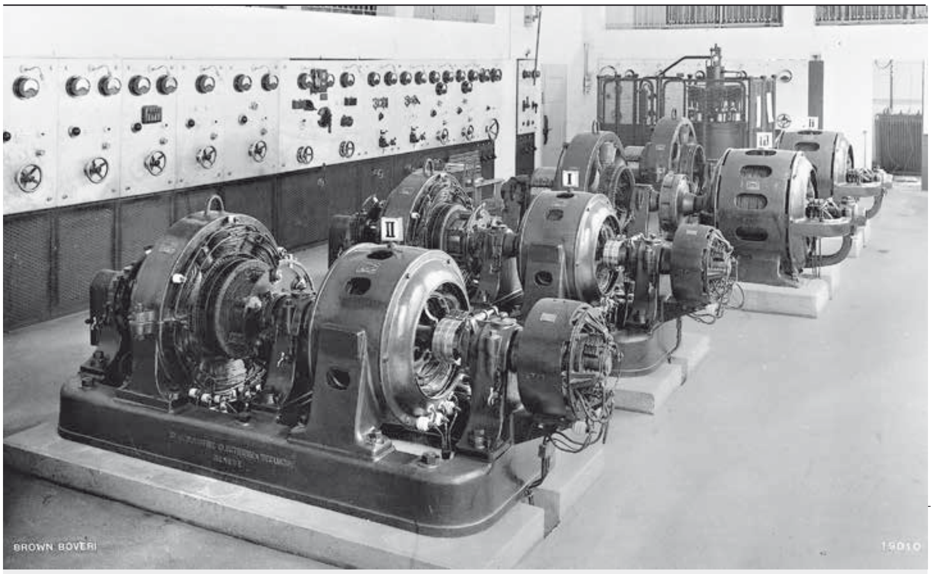
In 1908, the Hungarian engineer, Béla B. Schäfer commenced research on mercury-arc valves for the Frankfurt based company H&B (Hartmann & Braun). He registered the first of many patents in 1909 (his first patent was a solution to the challenge of embedding metal wires to cross the glass wall without compromising air-tightness). H&B was the first German company to supply a rectifier (delivered to a Frankfurt foundry in 1911). As H&B's main business lay in the manufacturing of scientific instruments and the company had little experience with industrial high-current applications, a joint venture was created with Swiss-based BBC (Brown, Boveri & Cie) in 1913. The new company was called GELAG (Gleichrichter AG) and based in Glarus, Switzerland. GELAG was mainly concerned with research and development, with BBC manufacturing the valves in Baden, Switzerland. In 1916, BBC also

4 Steel tank mercury-arc valves from BBC

4a Type HG 5/6 valve (1923) (420 A, 650 kW, 1,550 V and weighing 1,700 kg) as used for the Zweilütschinen electrification ➔ 5.

4b A large mercury-arc valve in steel tank. This 2,500 A, 2,000 kW example from the 1950s weighed 1,235 kg and was more than 3 m tall.

5 Electrification of Bernese Oberland railway




The Bernese Oberland railway, in the Jungfrau region of the Swiss Alps, was electrified by BBC using 1,550 V DC in 1913. Rectification was performed by motor-generators, with the DC supply being supported by a battery. In order to demonstrate its mercury-arc rectifier technology, BBC added such an installation in 1920, with the rectifier working in parallel to the motor-generators. The demonstration impressed the railway with its high efficiency and reliability, remaining in service for 2¼ years. It was replaced by a permanent installation in 1923.

The photograph shows the converter station in 1924 with in the foreground the two main 220 kW motor-generators behind them the two auxiliary 48 kW generators with controllable excitation, and in the background the single 650 kW mercury-arc rectifier, showing their much reduced spatial requirements.

Source: The mercury arc rectifier plant of the Zweilütschinen substation of the Bernese Oberland Railway. Brown Boveri Review, October 1925, page 214.

Semiconductivity was first recognized in silver sulfide by Michael Faraday in 1833, but the phenomenon was not fully understood until the early 1930s.

commenced production in Mannheim, Germany. German production was transferred to a larger factory at Lampertheim, Germany, in 1921 and joined by a second site that same year when BBC acquired the Berlin-based Gleichrichter GmbH (founded in 1919).

BBC took over H&B's stake in GELAG in the 1920s, and finally dissolved the latter in 1939, absorbing its activities into the parent company. Later, H&B also became part of ABB's heritage: The company was acquired by Elsag Bailey in 1995, which itself became part of ABB in 1999.

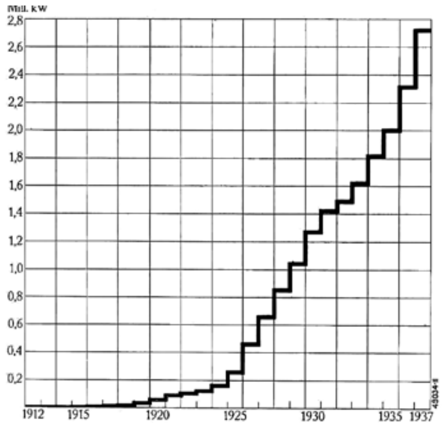
Schäfer left GELAG in 1921 and started his own consultancy. In 1927 he sold valve designs to ASEA (Allmänna Svenska Elektriska Aktiebolaget) for production in Ludvika, Sweden. Schäfer's expertise thus flowed into products of three of ABB's predecessor companies.

### Valve design and applications

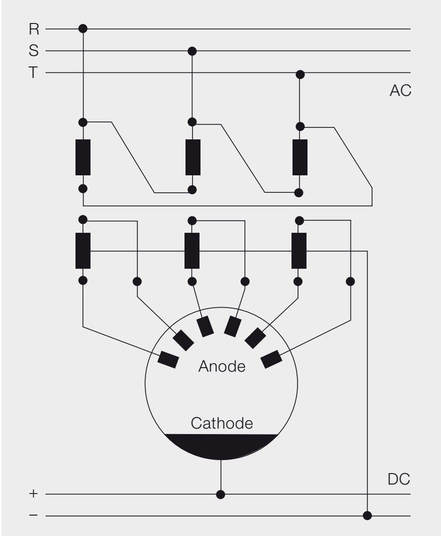
Due to the low thermal conductivity of glass, the power capability of a valve is restricted by its surface area ➔ 3. As power ratings increased, steel tanks (with isolated electrodes) were adopted instead ➔ 4. The market for mercury-arc valves boomed, and with it BBC's production ➔ 5–6. The company assumed a leading position in the development of the technology.

A simple rectifier circuit is shown in ➔ 7. It is equivalent to an H-bridge in which a single enclosure with six anodes performs the function of six discrete diodes.

6 The production of mutators was a rapidly growing business for BBC.




7 Mutator for rectification of three-phase AC




Whereas operation of such a valve could be sustained if the operating temperature was maintained within the limits and the arc was not permitted to fully extinguish, it could not start-up unaided when no plasma was present. A starting electrode (to which a high voltage pulse was applied) was thus provided to create the initial arc. The ability to trigger conduction at an arbitrary point in time had obvious potential for selective switching (the valves described in this article so far were all diodes). Development of such switchable valves commenced in 1930, enabling phase-fired controls (these valves fulfilled the same functionality that is today performed by thyristors – they can be switched on arbitrarily but must wait for the current to reach zero to extinguish). By connecting them in an H-bridge, a line-commutated inverter can be made. As the term "rectifier" became increasingly incorrect in view of such new applications, in 1934 BBC began referring to its valves collectively as "mutators".

With both rectifier and converter functionality now feasible, BBC built a temporary demonstration line for the 1939 Swiss National Exhibition and Trade Show. The 500 kW, 50 kV DC link had a converter station at either end and transmitted electricity 25 km from Wettingen to the company's exhibition pavilion in Zürich using a single pole cable → 8 (the return path being by earth conduction). This link was a precursor of today's HVDC technology.

It was ASEA, however, that built the world's first permanent and commercial HVDC link, connecting the Swedish island of Gotland to the mainland in 1954.

The manufacture of mercury-arc rectifiers continued until the mid 1960s → 9. Mercury valves were finally replaced by another revolution in power electronics: semiconductors. Advantages of semiconductors included greater power density and speeds, lower weight and losses as well as avoiding the toxic aspects of handling mercury.

## Semiconductors

The elements of the periodic table are generally divided into metals and nonmetals. In their pure form, metals conduct electricity, whereas nonmetals (mostly) do not. There is however an interesting group of nonmetals that display intermediate levels of conductivity. These are the semiconductor materials, most notably germanium and silicon. Some hybrid crystals such as gallium arsenide and silicon carbide also have semiconductor properties.

Semiconductivity was first recognized in silver sulfide by Michael Faraday in 1833, but the phenomenon was not fully understood until the early 1930s when the band theory of conduction emerged.

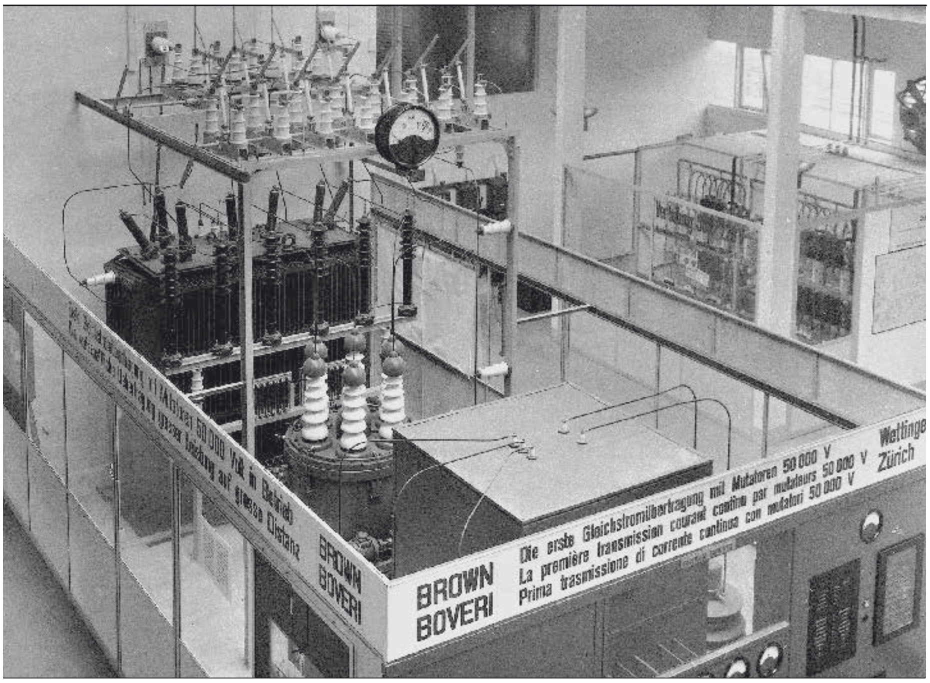
To raise the conductivity of semiconductor materials, impurities are selectively inserted into the crystal. These atoms occupy positions in the crystal lattice that an atom of the substrate material would otherwise occupy. If the inserted atoms have more electrons in their outer band than the host material (n-type), the "spare" electrons are free to move through the crystal and so increase its conductivity. If the inserted atoms have fewer electrons in their outer band (p-type), this creates so-called holes. Electrons from neighboring atoms are able to occupy these positions, which in effect leads to the holes themselves having mobility. Holes thus behave like positive charge carriers and also increase conductivity.

A simple example of a semiconductor device is a diode. A p-zone adjoins an n-zone on the same crystal. Current can flow from the p- to the n-zone (ie, in the p-zone holes flow towards the p-n junction, in the n-zone electrons flow towards the junction, with the two types of carrier recombining at the junction). If a reverse voltage is applied, charge carriers are depleted from the junction area and conduction ceases.

In order to create switchable valves, a method was required to externally trigger conductivity. The first transistor was created by Bell Laboratories in 1947. It used an electric field to control the availability of charge carriers in a germanium crystal, meaning that the current through it was determined by a control voltage.

The invention of the transistor kicked off a rapid and highly visible development culminating in the remarkable revolution

8 At the 1939 Swiss National Exhibition in Zürich, BBC demonstrated DC transmission using mercury-arc converters.




in communications and data processing, whose fruits (and ongoing developments) are highly visible today. Maybe less obvious but equally spectacular is another semiconductor revolution that occurred in parallel in the domain of power electronics: Today electricity can be transformed, controlled and converted in ways which only some decades ago would not have been considered possible. For example today's ubiquitous data and communications devices and their highly integrated microprocessor chips would be of little use without power-electronic circuits delivering their power, charging their batteries and keeping the datacenters and communications links running without which social networks and other online services could not function. Similarly, today's boom in renewable energy and the resultant reduction of emissions would not be possible without power-electronic converters assuring reliable and affordable grid connectivity.

It took many decades of development to make this feasible. Both BBC and ASEA commenced semiconductor development in circa 1954, with BBC's first rectifier diodes (rated 100 V, 100 A) coming onto the market in 1956. These and other early semiconductors were made of germanium[1], but the material was found to be unsuitable for power applications due to constraints in terms of blocking voltage and temperature. It was soon displaced by silicon.

## Thyristor

Transistor applications in analog amplifiers (such as in radios and telecommunications) are well known. However, the demands of power electronics are different: Switches should ideally either be on or off, with the transition period being kept as short as possible. This is because the losses in the device, and hence the heat generated, are the product of the current and the voltage, and so either one or the other must be kept as close to zero as possible – both in the interests of energy efficiency and to prevent thermal damage to the device.

An early switchable power semiconductor was the thyristor, whose principle was proposed by William Shockley in 1950. A thyristor is similar to the p-n diode described previously, but with additional layers inserted between the outer p- and n-zones. These layers normally prevent conduction, but the injection of current at a third contact (called the gate) floods this area with charge carriers, enabling current to flow if a forward voltage exists between anode and cathode. Once triggered, the replenishment of charge carriers is self-sustaining, mean-

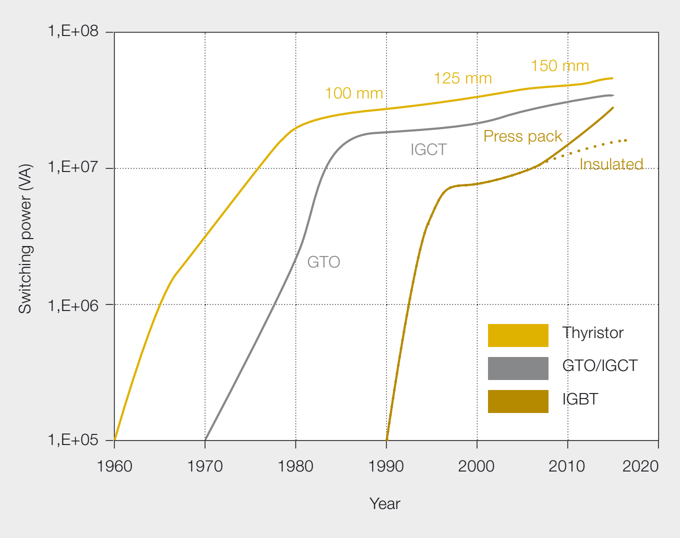
**Footnote**

1 Some manufacturers used selenium.

9 Milsestones of ABB's 100 years in power electronics

| | |
|---|---|
| **1913** | BBC commences production of mercury-arc rectifiers in Baden |
| **1915** | BBC supplies stationary rectifiers to Limmattal Strassenbahn (tramway in Zürich area) |
| **1921** | Production commences in Lampertheim, Germany (BBC) |
| **1924** | Switching theory by Dällenbach and Gerecke published (BBC) |
| **1928** | ASEA commences production of mercury-arc rectifiers in Ludvika, Sweden |
| **1938** | BBC (Mannheim) equips locomotive with rectifier (experimental 50 Hz electrification in Germany) |
| **1939** | BBC demonstrates experimental DC transmission Wettingen – Zürich → 8 |
| **1954** | First BBC germanium diode |
| **1954** | First commercial HVDC, Gotland link (ASEA) |
| **1960** | BBC's first thyristor |
| **1961** | HVDC link between Britain and France under English Channel (ASEA) |
| **1964** | First BBC locomotive with silicon diode rectifier (Re 4/4 for BLS), Switzerland |
| **1967** | First ASEA thyristor rectifier locomotive (Rc for Swedish Railways) |
| **1970** | Pacific Intertie, HVDC linking Celilo (Oregon) to Sylmar (Southern California) – the last major project to use mercury-arc valves |
| **1971** | Semiconductor manufacturing at Lampertheim commences (BBC) |
| **1973** | BBC opens research center at Dättwil, Switzerland |
| **1979** | HVDC link Cabora Bassa – Johannesburg (BBC in collaboration with AEG and Siemens) |
| **1981** | Semiconductor manufacturing at Lenzburg, Switzerland, commences (BBC) |
| **1984** | HVDC link Itaipu – Sao Paolo (ASEA) |
| **1987** | First BBC locomotives to use GTO converters (for BT and SZU, Switzerland) |
| **1988** | Merger of BBC and ASEA to form ABB |
| **1993** | Development work for BiMOS commences |
| **1996** | IGCT production commences |
| **1998** | BiMOS line opens in Lenzburg |
| **2004** | Three-gorges HVDC, China |
| **2010** | Acquisition of Polovodiče, Czech Republic |
| **2010** | New semiconductor factory in Lenzburg |
| **2012** | BIGT platform |
| **2012** | ABB announces hybrid breaker |
| **2013** | Work begins on new semiconductor reasearch facility in Dättwil |
| **2013** | ABB celebrates 100 years in power electronics |

10 Development of switching power of the three major power semiconductor device types

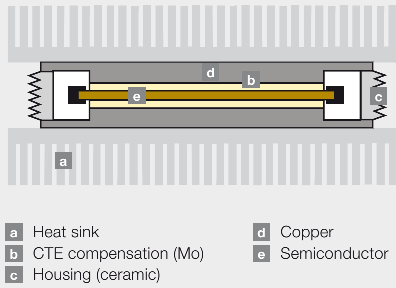



11 Lenzburg is the heart of ABB's semiconductor activities. The new BiMOS plant is the building on the right.


12 Semiconductor manufacturing in Lenzburg

13 Cross-section of a pressure contact device

In pressure contact modules, the load current enters through one surface d and leaves through the opposing surface. Low electrical and thermal resitances of the contacts are assured through high mechanical pressure on those surfaces.




ing the trigger current can be removed. Conduction does not cease until the current drops below a critical value. The device can thus be used for line-commutated inversion, but not for self-commutation (unless external components are used to artificially create a zero-crossing of the voltage).

Between 1960 and 1980, the maximum blocking voltage and power handling per device increased in a roughly linear fashion, from about zero in 1960 to 6,000 V and 600 kW in 1980 → 10.

## GTO

Production of GTOs commenced in the mid 1980s. A GTO (gate turn-off thyristor) is a thyristor that can be turned off by applying a current to the gate in the reverse direction to that required to turn it on. The ability to produce devices that were able to switch off without an artificial zero crossing helped expand the scope of application of power semiconductors, enabling for example DC-DC converters and self-commutated inverters. Furthermore, multiple switching cycles during an AC half-wave can make the AC output less rectangular in shape. The width of current pulses is varied to modulate the desired waveform, hence reducing harmonics.

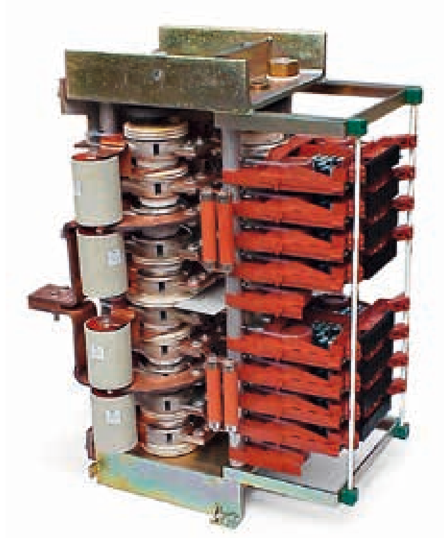
## Semiconductor production

BBC's early semiconductor production was at Ennetbaden, Switzerland. BBC established a modern semiconductor factory at Lampertheim in the late 1960s, and sought to concentrate all manufacturing there. However, some of the production at Ennetbaden (mostly development activities and pilot production, but also modest levels of production) was transferred to Birr, Switzerland. These activities were moved to a new factory at Lenzburg , Switzerland, in 1981.

Following the merger of ASEA and BBC to form ABB in 1988, the Lampertheim site was sold to IXYS, and ASEA's factory at Västerås, Sweden, was closed, with all production being concentrated at Lenzburg. ASEA's strength lay in thyristors and rectifier components with negative bevel design, whereas BBC's strength lay in diodes, GTOs and thyristors. Although there was some overlap, the different ranges were largely complementary.

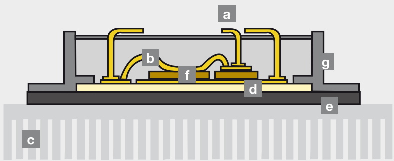
14 GTOs of different diameters

15 GTOs mounted in a stack with gate units and cooling elements



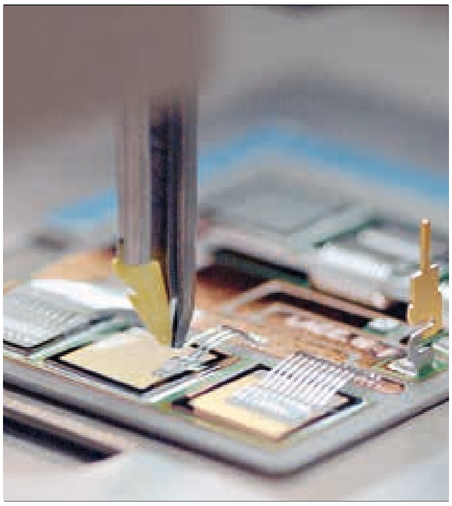
16 Cross-section of a Hi-Pak IGBT module

In insulated housing modules, the semiconductor f is galvanically isolated from the heat sink c. Electrical contacts within the module are provided by bonding wires.




- a Power and control connections
- b Bonding wire
- c Heat sink
- d Ceramic (usually AlN)
- e Base plate (usually AlSiC)
- f Semiconductor
- g Housing

17 Soldering of contacts to IGBT chips



At the time, semiconductor manufacturing was not recognized as a business in its own right within ABB, but was perceived as an activity for the support of other product areas, such as drives or HVDC. Product development and investment was thus largely driven by the needs of ABB's other businesses. All this changed rapidly when Anders Nilarp was appointed to lead ABB's semiconductor activities. He transformed the business into a standalone enterprise, directly competing with other semiconductor manufacturers on the outside market. His charismatic style also transformed the workings of the Lenzburg factory as he continuously sought to motivate and empower employees. In 1995, the Lenzburg factory was a finalist in the European Quality Award, and in 1996 it was awarded the "Supplier of the Year Award" by General Electric.

## IGBT

Nilarp's greatest achievement was the new BiMOS factory that opened in Lenzburg in 1998, specifically tailored for the manufacture of IGBTs (insulated gate bipolar transistor). The introduction of IGBTs represented a fresh leap in terms of manufacturing complexity and the technologies involved, but at the same time also represented a step change in device performance and capability. An IGBT is a power semiconductor controlled by voltage rather than current – thus also reducing the power and space requirements of the gate units (the external drive units that turn the switch on or off via the gate), permitting more compact and lightweight converters. IGBTs are also more inherently stable than GTOs, reducing the need for protective circuitry, and are furthermore capable of faster operation, permitting higher switching frequencies.

## IGCT

To also make hard-switching capability available for higher power classes, ABB pioneered the IGCT (integrated gate-commutated thyristor) in the mid 1990s. Developed on the basis of GTO technology, the new device was capable of much faster switching than conventional GTOs. In this it was supported by an integrated low-inductance gate unit. This development was remarkable as it occurred at a time that other manufacturers were withdrawing from GTO development, assuming the technology had no future.

ABB further strengthened its market presence with the acquisition of the Czech semiconductor company, Polo-

18 Hi-Pak IGBT modules

19 StakPak IGBT modules

vodiče, in 2010. This gave ABB a second manufacturing site (in Prague). At the same time, capacity at Lenzburg was again increased with the construction of a further factory → 11.

## Manufacturing and design

The manufacture of semiconductors is a highly sensitive process. The silicon base material must be of a very high quality with extremely low levels of contamination. The insertion of the necessary p- or n-materials (doping) is a very precise process requiring the correct duration and temperature. Manufacturing thus occurs in so-called clean-rooms characterized by a carefully controlled atmosphere to keep contamination levels as low as possible → 12.

Most larger semiconductors (including thyristor, GTO and IGCT) feature a so-called free-floating housing. The silicon wafer is sealed inside a ceramic shell with copper contacts → 13–14. The contacts must be pressed against the silicon by a specified external force to assure optimal electric and thermal conductivity. To assure this force, devices are mounted in stacks → 15, with cooling units usually interspersed in the same stack. Devices are designed to short-circuit when they fail. A typical stack with series-connected devices will thus have some redundancy, permitting normal operation to continue until the next scheduled maintenance intervention.

The introduction of the IGBT marked a departure from this practice. Rather than using large area-wafers, IGBT modules feature larger numbers of small chips. Contact wires are soldered directly onto the chips → 16–18, eliminating the need for pressure-mounting in stacks and thus simplifying converter assembly while reducing weight and space requirements and making it easier to exchange individual modules during maintenance. However, IGBTs are also provided in press-pack housing for applications requiring such assemblies (StakPaks) such as for HVDC → 19.

## BIGT

The latest development of the IGBT family is the BIGT (bimode insulated-gate transistor), an IGBT that integrates the reverse-conducting diode in a highly space saving manner (the BIGT is discussed more fully on pages 19–23 of this issue of *ABB Review*). The BIGT is an important component of one of ABB's most significant announcements of recent decades: the hybrid circuit breaker (discussed on pages 6–13).

The hybrid circuit breaker is a further example of semiconductors finding their way into entirely new uses. The range of applications of power electronics is growing in ways that only some years ago would have seemed unimaginable.

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**Further reading**

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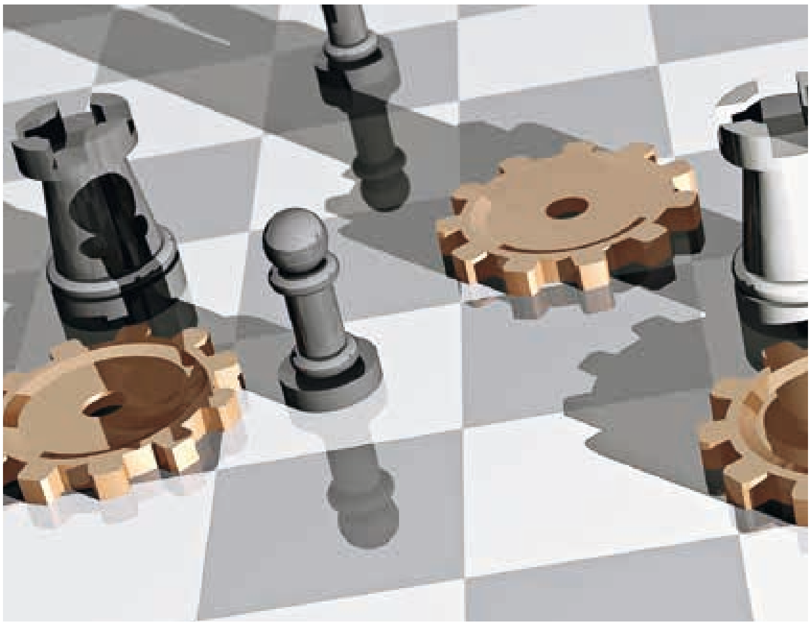

Preview 3I13

# Simulation

With technologies advancing to greater sophistication, systems growing in complexity, and the scope of interaction between components increasing, the challenges of testing are also facing steep growth. Although simulations cannot fully replace testing, there are many situations where simulation can save time and costs (as well as prevent potentially dangerous situations). Simulation also permits a greater understanding of processes and thus permits higher levels of optimization to be achieved. Increases in computer power and algorithmic advances mean that more and more systems can be, and are being, simulated. Besides supporting design and engineering, simulations can also be used to train operators and analyze hypothetical situations.

Issue 3/2013 of *ABB Review* will focus on the theme of simulation, showing how ABB is using and developing the technique to improve the timely and qualitative delivery of systems and solutions to customers.

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