

ABB

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The corporate
technical journal



Two anniversaries

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The year 2016 marks a double anniversary for ABB. On the one hand, the company celebrates 125 years of its presence in Switzerland. ABB's predecessor company, BBC, was founded in 1891. On the other hand, the year is the 100th anniversary of Corporate Research. ASEA founded its first dedicated research center in Västerås, Sweden, in 1916.

The front cover shows the stator of a 22MVA generator supplied by ASEA for Glomfjord, Norway, in 1919. The inside cover shows the stator of a modern wind power generator being manufactured in Lingang (Shanghai), China.

Two anniversaries

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Reflecting on the future



Bazmi Husain

Dear Reader,

It is said that the only true constant is change. In probably no other field is this better exemplified than in technology.

When seeking to understand and contextualize the longer term dynamics and ramifications of change, history is often the best perspective to study it from. The present digital revolution is sometimes referred to as Industry 4.0 in reference to three previous industrial revolutions, ie, mechanization (late 18th century), mass production (early 20th century), and electronics-based automation (late 1960s). Each of these revolutions unleashed fundamental changes, not only on industry itself but also on the underlying economic systems, society and even thinking. To those who are willing to embrace them, revolutions are times of opportunity opening new fields of application, many of which could previously not have been imagined.

ABB has lived through the beginnings of three of the four great industrial revolutions, and has stood out as a leader in them. For example in 1974 the company launched the IRB-6, the first all-electric and microprocessor controlled robot. This breakthrough enabled fundamental paradigm shifts in different areas of manufacturing with huge repercussions for workplace safety and productivity.

This year, ABB celebrates a double anniversary. It was 125 years ago, in 1891, that Charles Brown and Walther Boveri (the two B's of our company's name) founded an enterprise that was to become a predecessor of today's ABB. They soon took a leading role in the generation, transmission and conver-

sion of electrical energy. Electricity was no new invention, but recent breakthroughs had made it possible to transmit it economically and so bring about huge advantages affecting both personal lives and industrial capability. The situation can be compared to today's digital revolution. Neither the microprocessor nor wireless communications are genuinely recent inventions, but it took a perfect storm of affordability combined with visionary thinking to unleash their potential.

The second significant anniversary of this year is the centenary of the company's corporate research. In 1916, ASEA (ABB's other predecessor company and the A of our company's name) opened its first dedicated research facility in Västerås, Sweden. The achievements of this center include early synthetic diamonds as well as groundbreaking contributions to automation and HVDC systems. Research centers embody ABB's resolve to stay ahead through excellence in research. Today ABB employs some 8,500 people in its R&D activities worldwide.

Our look back at ABB's history is at the same time a look forward at the challenges and solutions ahead. I trust that in reading this issue of ABB Review you will discover inspiring examples of both.

Enjoy your reading!

A handwritten signature in blue ink, appearing to read 'Bazmi Husain', written in a cursive style.

Bazmi Husain
Chief Technology Officer
ABB Group





125 years and a centennial

ABB celebrates 125 years' existence in Switzerland and 100 years of corporate research

DOMINIC SIEGRIST – 2016 is a momentous year for ABB. Not only does it mark 125 years since the birth of Brown Boveri & Cie. (BBC) Switzerland, but it also sees the centenary of ASEA's corporate research organization in Sweden. Over those years, an astounding amount of technological progress has been made by BBC and ASEA – both separately and together (since 1988) as ABB. There will be celebratory events around the globe and some of the more important advances will be described in detail in this and subsequent editions of ABB Review. It is worth taking a brief look at some of the technical highlights of BBC over the past 125 years and some technical achievements of the Swedish research organization in the past decade.

Power and automation for a better world™ is the ABB corporate motto. Even in the earliest days, the products developed by ABB's main constituent companies reflected the ethos expressed by this maxim.

In 1883, ASEA was founded in Västerås, Sweden, by Ludvig Fredholm. ASEA's very first products – for electric light and generators – very much contributed to a better world. Similarly, when, in 1891, Charles Brown and Walter Boveri created Brown Boveri & Cie. in Baden, Switzerland, their electrical products facilitated major improvements in the lives of many millions. Indeed, by making the widespread use of a brand-new resource – electricity – possible, the products developed by these two progenitors of ABB made a major contribution to the greatest technological change society had ever seen → 1.

BBC technological breakthroughs came rapidly: In 1891, the first power station in the town of Baden was built; in 1895, the tram system in the Swiss city of Lugano was provided with electrical equip-

ment → 2; in 1897, there came the first of many high-voltage oil circuit breakers → 3; and by 1911, the company had developed an electrically powered locomotive that ushered in a new era of railway electrification. In fact, locomotives formed a significant part of BBC's research and development effort right up until the end of the 19th century.

In 1905, BBC suggested to the SBB (the Swiss national rail operator) that the Simplon Tunnel, then under construction, should be electrified. The SBB declined and BBC offered to do the job at its own cost. Although not a financial success,

By 1911, BBC had developed an electrically powered locomotive that ushered in a new era of railway electrification.

the project resulted in the world's first international electrified train link and the experience gained gave BBC's railway electrification business a massive boost, as was evident by the many contracts won in the subsequent years, including the huge order for the Gotthard Tunnel some 15 years later → 4.

Title picture

Size was no obstacle to BBC and ASEA. Shown is a BBC 2 MW three-phase AC generator in a German steelwork, in 1912.

ASEA and ABB products facilitated major improvements in the lives of many millions.

1 Walter Boveri, accompanied by his wife (middle) and an acquaintance, inspecting the construction of the first factory building, 1891.



Between the wars

The period 1918–1939 proved to be stormy. After a worker and raw material shortage during World War One, BBC experienced a short boom up until 1920, when there was nearly a complete collapse in orders for some years. The subsequent recovery was short lived as the Wall Street Crash of 1929 wreaked further havoc. Once again, however, the business bounced back and in 1939 the first shareholder dividends for seven years were paid out.

BBC – war and expansion 1939 to 1970

In 1936, BBC had become a late entrant to the radio market but succeeded in quickly establishing itself, with its first transmitter valve appearing in 1939. Valve production was moved from the laboratory to a specially constructed factory in 1943. Valve technology gradually expanded from purely radio transmission to heat generation for industrial applications and radiotherapy. This was to culminate in the development of a clinical electron accelerator (Betatron) by the end of the decade.

In 1939, BBC built the world's first gas turbine, which served the town of Neuenburg as an emergency generator until as recently as 2002. It now adorns the pavilion of the ALSTOM works in

Birr, Switzerland as a proud reminder of BBC's history.

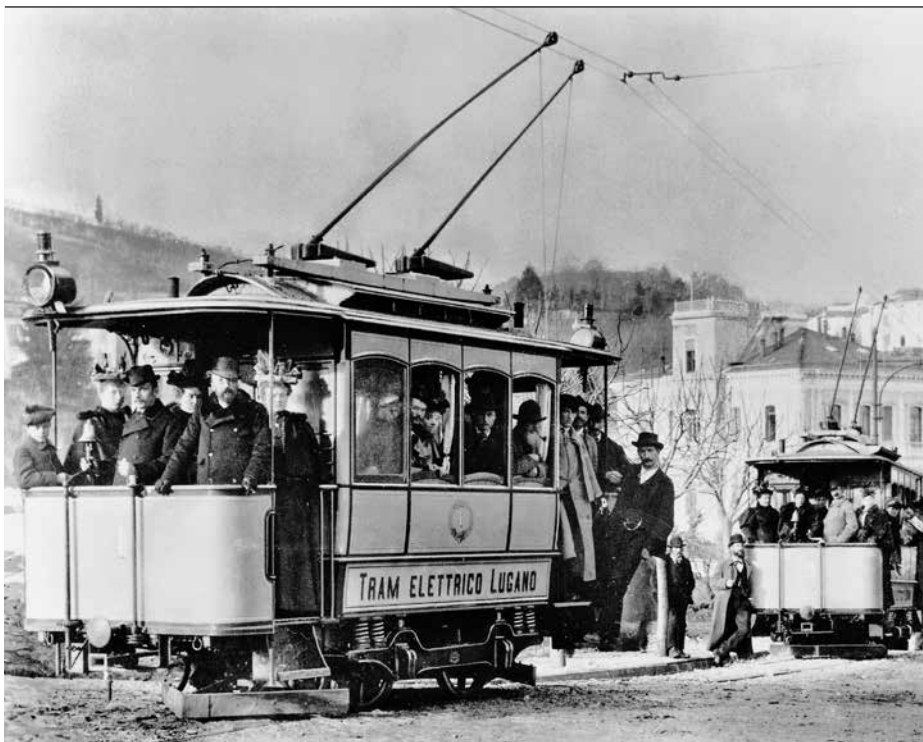
The outbreak of World War Two threw the company into renewed turmoil. Once again, there was a shortage of workers due to military conscription, even as orders grew. The company found itself in a delicate situation, supplying both the allies and the Third Reich. However, home orders rose to record levels (40 percent of all orders were delivered to Swiss customers in 1942/43) – especially in power generation products. Moreover, Spain, rebuilding after the civil war, became one of BBC's largest customers. In the midst of World War Two, the company managed to find the resources and time to build the high-voltage laboratory in Baden – a facility that was to prove invaluable in years to come.

By 1935, BBC in Mannheim, Germany, had grown to dominate the original site in Baden. Business flourished with orders

for war material: U-boat drives, warship turbines, jet engine compressors, etc., but heavy bomb damage in 1944 subdued activity, though the company was flourishing again within ten years' of war's end.

Toward the end of World War Two, orders exceeded capacity and when the war ended in 1945, the company found itself in a favorable business position as most divisions expanded. The mid-1950s saw a boom in steam turbines, with systems of unprecedented power and massive orders from customers such as the Tennessee Valley Authority (who were to receive a record-beating 1,300 MW BBC turbogenerator in 1967). Turbochargers saw similar growth – both in business volume and technical capability.

In 1953, BBC's specialized laboratory for aerodynamics and combustion research was opened. 1965 saw BBC bring out the world's first water-cooled hydro-



The Simplon electrification was the world's first international electrified train link and the experience gained gave BBC's railway electrification business a massive boost.

generator. On the domestic front, BBC produced cookers, washing machines, humidifiers and bed warmers – this business arm was sold to AEG in 1972 (though BBC continued to make coffee machines until the 1980s).

Like the BBC story above, ASEA also has a history studded with technical breakthroughs. In this, the 100th anniversary of the founding of the ASEA's corporate research arm, it is worthwhile to look back at some of the momentous products that the organization has produced in the past decade or so.

Driving progress

By the late 1960s, the pace and breadth of both ASEA and BBC's technological progress had increased significantly and advances in electronics were opening up entirely new ways to approach industrial problems. An early example of the benefits delivered by electronics was the digital variable-speed drive (VSD).

Electric motors are ubiquitous in industry. In fact, about two-thirds of all the electrical energy produced in the world is converted into mechanical energy by electric motors. The vast majority of these motors are used to power fans, pumps and compressors. Most of these applications operate at constant speed,

all the time, even when not needed, using throttles or valves to control the flow of fluids or gases. This represents a huge waste of energy.

Enter the VSD. Launched in 1969, and equipped with a revolutionary technology called direct torque control (DTC), VSDs adapt the speed and torque of the motor according to the precise needs of the application. Typically, energy savings of around 50 percent can be achieved and control quality improves.

In 2011, ABB made another significant step in motor technology with its synchronous reluctance motor (SynRM).

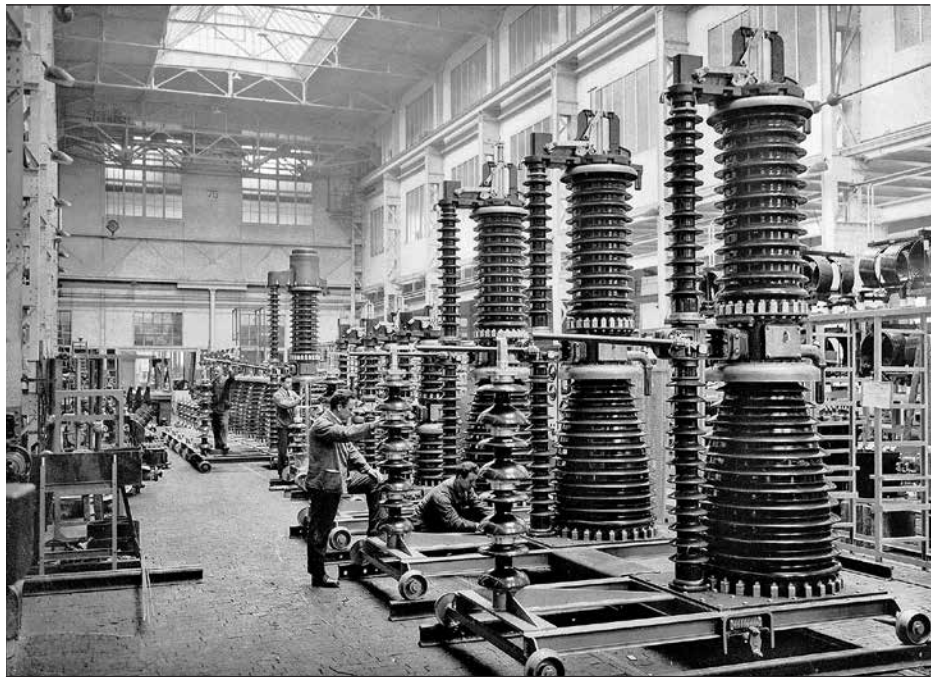
SynRM

Induction motors (IMs) are by far the most common motors in industry. This powerful and efficient motor does not have a commutator or brushes, which makes it reliable and relatively maintenance-free. However, it has certain drawbacks, which can be overcome by the permanent magnet (PM) AC motor.

PM motors only became competitors to IMs in the 1980s with the creation of a new generation of permanent magnets based on rare-earth elements (REEs) such as neodymium iron boron (NdFeB). (Note that such motors need sophisti-

In 1967, the Tennessee Valley Authority took delivery of a record-beating 1,300 MW BBC turbogenerator.

3 High-voltage switch manufacture in 1935



cated AC drives – another area of ABB innovation.) The PM motor is synchronous, meaning the rotor rotates in synchronism with the magnetic field. This offers more precise speed control, higher efficiency, lower rotor/bearing temperature and a host of other advantages.

There is, of course, a catch: REEs are costly and can be subject to price variations. In addition, their strong magnetic rotor field can make servicing more difficult.

In recent years, ABB introduced two REE-free motors – SynRm → 5 and the permanent-magnet-assisted synchronous reluctance motor (SynRM2, introduced in 2014), which use ferrite magnets.

SynRMs perform better than conventional IMs. They can be designed for high-efficiency performance or to provide a higher power density for a smaller footprint than an equivalent IM. They need less maintenance, have a reduced inertia and are extremely reliable.

Softstarters

One of the drawbacks of the IMs mentioned above is the problem of starting them. The most common starting method is the direct-on-line (DOL) start using a main contactor and a thermal overload relay. Unfortunately, this leads to a starting current that can be six or seven times the rated current.

Just over 30 years ago, ABB introduced the softstarter. A softstarter reduces the torque to the electric motor as it starts. This reduces voltage drops on networks, minimizes starting currents, eliminates current spikes and allows cabling to be optimized.

In the intervening years, ABB has refined the softstarter concept with new models continually released to the market. 2010 saw the introduction of the very successful PSE model; in 2014 the PSTX offered new communication features and a new operator interface that gives diagnostic information.

The direct approach

Around the same time that ASEA and BBC came into existence, the War of Cur-

An early example of the benefits delivered by electronics was the digital variable-speed drive.

rents was taking place. This pitted Edison's established direct current (DC) technology against the new alternating current

4 A novelty in 1919: An electric locomotive for the Gotthard Tunnel line on a test drive at Thun, Switzerland.



(AC) approach championed by, among others, Westinghouse (later part of ABB). Initially, because it was more efficient to transmit and easier to handle, DC was the standard method of medium-voltage (MV) power distribution. However, AC technology soon came to dominate.

Recent technical advances – especially in semiconductor technology – have allowed DC back onto the stage. This factor, coupled with the need to shift vast quantities of electrical power around the globe, provided a significant driver for ABB to introduce high-voltage DC (HVDC) technology, the key technology of which is the series connection of insulated-gate bipolar transistor (IGBT) press-packs.

The power needed to control an IGBT is very low and can be taken from the snubber circuit connected in parallel with the IGBT. Therefore, no auxiliary power from ground level is needed. Moreover, the device's gate unit can very precisely turn the IGBT off and on, thus making it possible to connect the IGBTs in series and control hundreds of IGBTs individually in a fraction of a microsecond.

This technology formed the basis of HVDC Light, launched in May 1997, based on two-level converters working up to around ± 80 kV. Nineteen years after the first tentative steps, ABB's HVDC Light is a billion-dollar business

with 25 HVDC Light installations around the world, transferring over 10 GW.

Transformers

ABB has been a leader in transformer technology for many decades. The most recent advances are in the area of ultra-HVDC, with power transformers rated at up to 1,100 kV.

A transformer often has to have a tap changer and this is another pioneering field for ABB that has continued to see constant progress over the years. ABB's newest vacuum on-load tap changers reduce maintenance requirements and improve performance by ensuring that the electrical arcing that previously took place in the insulating oil now takes place in a vacuum interrupter, thus preventing arcing from contaminating the oil.

HVDC cables

HVDC power is not only carried by overhead transmission lines, it is also carried by cables – for example, to bring power from offshore wind farms or to link national grids across a sea. The practical length of AC cables is limited by capacitive effects, so the future of long-distance power transmission lies with HVDC technology.

Over the last 30 years, ABB has made significant technical progress in HVDC cables – for instance, with a 525 kV extruded cable system, launched in 2014, that is based on high-quality cross-linked polyethylene (XLPE). ABB has also developed a dynamic cable structure for HVDC – especially useful for offshore platforms.

Hybrid breakers

HVDC systems have to be disconnected if a fault arises. Today's HVDC installations are mostly point-to-point and can be disconnected by AC breakers at each end. However, this means the entire line is dropped. Once HVDC grids become commonplace, a fault could cause the entire grid to be dropped. A further complication is that disconnection has to happen much more quickly in a HVDC system than in a corresponding AC system.

These factors provided the motivation for ABB to develop its hybrid breaker. Once again, the benefits of power semiconductors were exploited: The ABB hybrid circuit breaker consists of a main breaker built of power electronic switches and surge arresters, and a parallel branch containing an ultrafast disconnecter (UFD) and power electronic load commutating

The power needed to control an IGBT is very low and can be taken from the snubber circuit connected in parallel with the IGBT.

switch. This “hybrid” allows fast disconnection suitable for HVDC applications.

Automation

Power is one pillar of ABB technology; automation is the other. It is no exaggeration to say that advances made by ABB changed the face of industrial automation. Not only did the company produce innovations in digital control systems (DCSs) and plant automation but ASEA was responsible for the world's first commercially successful electrical industrial robot, in 1973.

Early attempts at robotics by others, in the 1950s and 1960s, had resulted in clumsy, noisy, hydraulic beasts that

The key HVDC technology developed by ABB was the series connection of insulated-gate bipolar transistor (IGBT) press-packs.

5 The unique SynRM rotor



leaked copious amounts of oil. In the early 1970s, ASEA recognized the potential of electrically driven robots and proceeded to develop and market the world's first – the IRB 6 (Industrial RoBot/6 kg payload). As soon as it appeared, the IRB 6 was a success. The first order was to a small Swedish company and four of the five they ordered are still working in the same place, doing the same job, more than 40 years later – a testimony to the excellent design.

Following on from the IRB 6, whole new generations of ABB robots have been developed for automation tasks in many different industries.

Continued innovation all around the world

ABB's power and automation technology has been inspired by challenges in all possible spheres – in homes and offices, oil and gas fields in remote deserts, water treatment plants, underground in mines, deep beneath the sea (with transformers that work at depths of 3,000 m, for instance), in crowded, cramped cities, in fields and in manufacturing and processing plants that have changed beyond all recognition in recent years. ABB technology is even circling the globe in a satellite.

A significant new area of challenge – one that would not have been foreseen by Brown, Boveri or Fredholm – is climate change. The intellectual energy now being devoted toward mitigating anthro-

pogenic effects on climate has created entirely new areas of innovation for ABB.

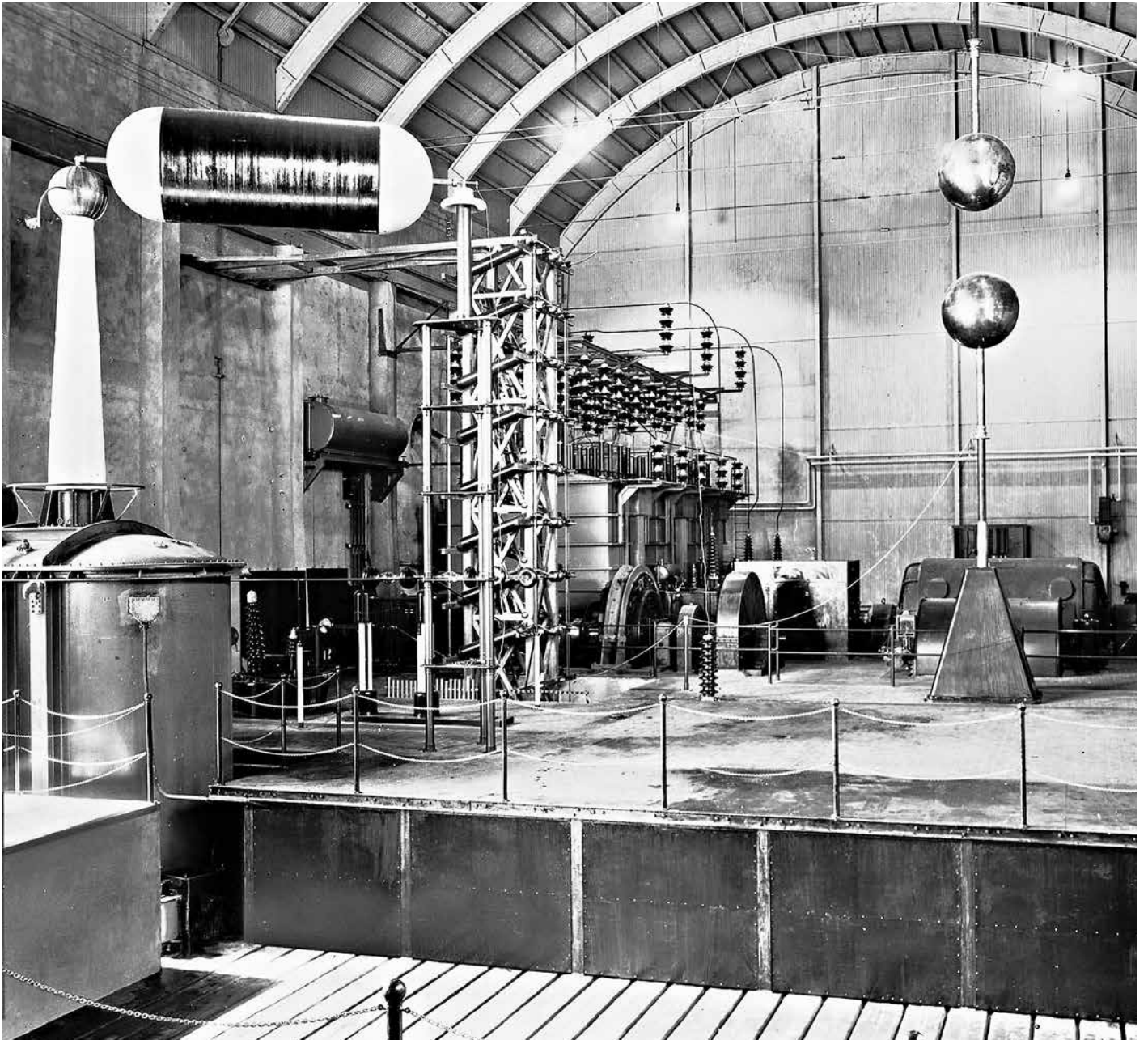
Renewable energy is one such area. Wind, solar, biomass, and other forms of generation have challenged ABB to come up with power and automation solutions.

In addition to the generators themselves, distributed renewable power generation and its attendant technologies – such as microgrids, energy storage, load balancing, power conditioning, marketing, scheduling and so on – are other areas that have seen the effects of ABB innovation.

Since the merger of ASEA and BBC in 1988 to form ABB, the company has retained technology and market leadership in many areas by continued innovation in power and automation. Many of the benefits of modern life were made possible by the efforts of ABB researchers over the past 125 years.

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Brainforce one

100 years of ABB's
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Research Center

ANDERS JOHNSON – Necessity, it is said, is the mother of invention. In the First World War, ASEA (ABB's Sweden-based predecessor company) found itself cut off from its materials suppliers. The company had to think hard and act fast to find alternative ways of meeting customer needs. It did this by establishing its Central Laboratory (as it was called at the time) in Västerås, Sweden, in 1916. An institution had been created that was not only to outlive the crisis from which it had emerged, but has successfully adapted to fresh challenges and changing paradigms throughout the following 100 years. Achievements include the world's first synthetic diamonds (1950s), the first electric industrial robot (1970s) and a series of landmark innovations establishing ASEA – and later ABB – as a pioneer and leader in HVDC. Today the center is working on several major projects in power and automation technologies that set out to increase sustainability.



1a Starting in 1949, ASEA launched a top secret project for the creation of synthetic diamonds. The first success was achieved in 1953 when a pressure of 8.4 GPa was maintained for an hour and the first diamonds were obtained. The project was kept so secret that results were not reported until the 1980s.



1b Early synthetic diamonds from the ASEA research center.

The center's initial task lay in materials research in order to find alternative materials as the First World War cut off established sources and disrupted supplies. The war ended, but the need for research remained.

The interwar period saw the Central Laboratory adopt a primarily supportive role for ASEA's manufacturing units. The laboratory typically took on challenges that were found to recur in many different parts of the company, such as questions relating to material strength and corrosion. But the lab also conducted qualified research and development, including into electrical insulation and high frequency furnaces.

During World War II, the Central Laboratory underwent major expansion. With supply channels once again disrupted and materials in short supply, the center returned to the development and testing of replacement materials.

In the 1950s → 1, ASEA began creating "a new science city" in Västerås. Several modern laboratory buildings were built in the Tegner neighborhood. In the early 1960s, the entire Central Laboratory was housed on the Tegner site, which is still used by Corporate Research today.

In the 1960s, the Central Laboratory had three main tasks: Firstly, material control. Secondly, workshop service and consulting; including new manufacturing meth-

Achievements include the world's first synthetic diamonds (1950s), the first electric industrial robot (1970s) and a series of landmark innovations establishing ASEA – and later ABB – as pioneer and leader in HVDC.

Title picture

ASEA's short-circuit test lab in Ludvika, Sweden (built 1930–33). The short-circuit tester in the background could develop a short-circuit power of one million kVA.

ods, control of engineering processes and troubleshooting. Thirdly, research and development, including related materials problems, manufacturing, machine and device structures and systems → 2.

2 An early 1980s HVDC thyristor valve for the Inga – Shaba intertie project in Zaire (today, Democratic Republic of Congo).



3 ASEA's IRB 6 was first presented in 1974. It had 5 axes and a payload of 6 kg. Many of the 1,900 examples built are still in use today.



In the mid-1960s the laboratory was involved in 70 major research projects. The most significant of these looked into fuel cells.

By the mid-1960s the laboratory was involved in 70 major research projects. The most significant of these was concerned with the development of fuel cells for submarines. The project turned out to be too far ahead for its time and had to be shelved. In the 1970s attention turned to industrial robots → 3. As well as digital speed control for paper machines and rolling mills. In 1980 the center was pivotal in developing fiber optic sensors to measure the temperature inside transformers.

In 1988, ASEA and Brown Boveri merged to form ABB. One of the most successful development projects in the 1990s was HVDC Light, of which the first com-

mercial installation was delivered to Gotland 1999.

Innovations of the 2000s with important participation by the Corporate Research center include:

- 2008: launch of groundbreaking vacuum tap changers for transformers.
- 2010: transformer for 800 kV ultra-high-voltage direct current (UHVDC)
- 2011: ABB demonstrates the revolutionary synchronous reluctance motor (SynRM).
- 2012: ABB announces the world's first circuit breaker for high voltage direct current.
- 2014: ABB sets world record with its new 525 kV HVDC cable.
- 2014: completion of a comprehensive project at the mine in Garpenberg making this the most efficient mine in the world.
- 2015: launch of two-arm industrial robot YuMi.

The following articles explore individual technology areas and achievements of the Research Center in greater detail. The celebrations of 2016 are as much about the future as they are about the past. As the center's centenary slogan proclaims, "the best is still to come."

In 1980 the center was pivotal in developing fiber optic sensors to measure the temperature inside transformers.

Anders Johnson
Historical writer
Stockholm, Sweden

Please address enquiries concerning this article to
Erik Persson
erik.persson@se.abb.com



Driving ideas

Electric motors represent a field rich in ABB innovation

Electric motor technology was introduced well over a century ago, with ABB being one of the major pioneers. The field has seen repeated bursts of innovation – a trend that not only continues to this day but that has also intensified during the last five years. Variable-speed drives (VSDs), direct torque control (DTC), softstarter and completely new kinds of motor that pack unprecedented amounts of power into a small volume are just some of the advances that ABB has brought to this area of technology.

In 2012, pumps, fans and compressors accounted for 79 percent of the world's low-voltage (LV) motor market by revenues [1]. LV motors dominate energy conversion too – 28 to 30 percent of all available electrical energy is converted to mechanical energy in LV motors – so special attention is paid to their efficiency and all major industrialized regions have minimum efficiency performance standards for them. The sheer quantity of power consumed by these devices around the globe makes it clear why the conversion of electrical energy to movement in an electric motor is such a fertile area of innovation.

Reference

- [1] M. Meza, "Industrial LV Motors and Drives: A Global Market Update – January 2014, IHS," presented at Motor and Drive Systems 2014 – Advancements in Motion Control and Power Electronic Technology, Orlando, FL, 2014.

Title picture

The efficiency and power density delivered by ABB's new SynRM and SynRM² represent a significant advance in electric motor technology. SynRM is just one area of ABB innovation in electric motors and electric motor control.

Driving ideas

Digital variable-speed drives

SJOERD BOSGA, HECTOR ZELAYA DE LA PARRA – AC motors have been the workhorses of industry for well over a century and are, by far, the most common electric motor found in industry today. However, in the past, AC motors could not be controlled as easily as DC machines, in which the motor torque is proportional to the armature current, making them simple to control. The evolution of AC VSD technology has, therefore, been partly motivated by the desire to emulate the characteristics of the DC drive – such as fast torque response and speed accuracy – while utilizing the advantages offered by the standard AC motor.

The basic function of a VSD is to control the torque or speed of an electric motor shaft. DC motors can be used as VSDs because they are easy to operate (they do not need sophisticated control electronics), and can effortlessly achieve the speed and torque required. However, the advent of power electronics a few decades ago made effective AC VSD technology possible and allowed the excellent performance of the DC motor to be emulated while using rugged, inexpensive and maintenance-free AC motors.

Traditional VSD approaches

AC drive frequency control uses voltage and frequency references fed into a modulator that simulates an AC sine wave and feeds this to the motor's stator windings. This technique is called pulse-width modulation (PWM) and utilizes the fact that there is a diode rectifier toward the mains and the intermediate DC voltage is kept constant. An inverter controls the motor in the form of a PWM pulse train dictating both the voltage and frequency → 1. Significantly, this method does not need a feedback device that takes speed or position measurements from the motor's shaft to feed them back into the control loop. Such an arrangement, without a feedback device, is called an open-loop drive. This approach

The advent of power electronics a few decades made effective AC VSD technology possible.

is low-cost, simple and is suitable for applications that do not require high levels of accuracy or precision, such as pumps and fans.

Another common approach, with better performance, is called flux vector control using PWM. However, this method is more costly and needs a feedback signal.

DTC

ABB's revolutionary DTC technology has many advantages over traditional methods of motor control. For example, field orientation is achieved without feedback – by using advanced motor theory to calculate the motor torque directly – and without using modulation. The controlling variables in DTC are motor magnetizing flux and motor torque.

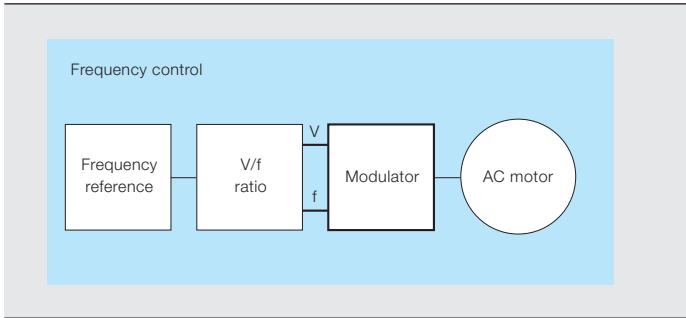
Further, with DTC there is no modulator and no requirement for a tachometer or position encoder to feed back the speed or position of the motor shaft → 2. DTC uses the fastest digital signal processing hardware available and an advanced mathematical understanding of how a motor works. The result is a drive with a torque response that is typically 10 times faster than any AC or DC drive → 3–4. The dynamic speed accuracy of a DTC drive is eight times better than any open loop AC drive and comparable to a DC drive that is using feedback. DTC makes possible the first “universal” drive with the capability to perform like either an AC or DC drive.

DTC makes a major contribution to energy savings, torque response, linearity and repeatability, motor speed accuracy and harmonic reduction.

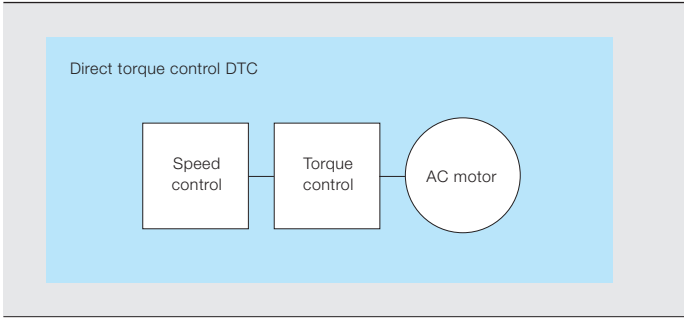
ABB's VSDs

The PWM frequency drive was first developed by Strömberg in Finland in the early 1960s. SAMI was Strömberg's brand name for variable-frequency drives, but this brand name disappeared when ASEA bought Strömberg in 1987. Over the decades, successive generations of improved power electronics have resulted in new families of ABB VSDs and an expansion of VSD application areas. In

1 Control loop of an AC drive with frequency control using PWM



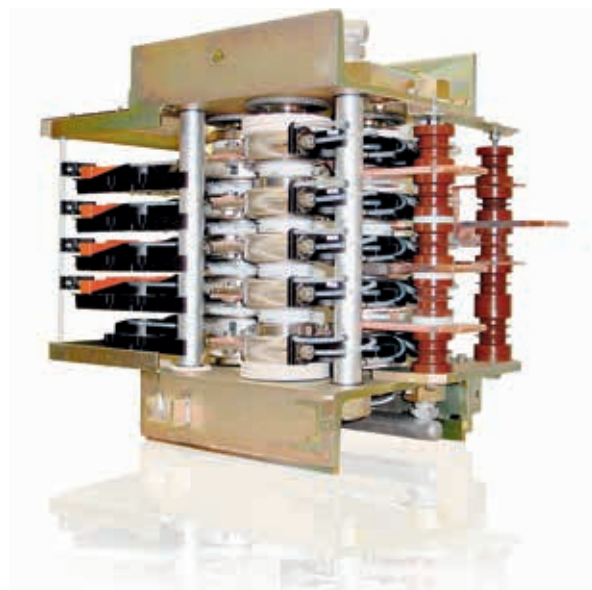
2 Control loop of an AC drive using DTC



3 ABB ACS550 drive controller



4 An ABB 9 MVA power electronic building block



ABB's revolutionary DTC technology has many advantages over traditional methods of motor control.

medium-voltage drives, the trends are toward reduced footprint, increased reliability and redundancy, and improved energy efficiency. With ABB's contribution to the field – the use of IGCTs (integrated gate-commutated thyristors) and DTC, for example – it is little wonder that ABB is one of the world's largest suppliers of VSDs to industry.

Sjoerd Bosga
Hector Zelaya De La Parra
ABB Corporate Research
Västerås, Sweden
sjoerd.bosga@se.abb.com
hector.zelaya@se.abb.com

Driving ideas

Softstarters

HECTOR ZELAYA DE LA PARRA, MARIA WIDMAN, SÖREN KLING, GUNNAR JOHANSSON – AC induction motors are the most common motors in industry. Very often, they are started using a main contactor and a thermal overload relay – the so-called direct-on-line start. However, this approach causes a starting current that can be a multiple of the rated current. This inrush current may cause voltage dips that impact other loads. Also, extreme mechanical stresses can be experienced during start-up that can lead to damage. Softstarters provide an alternative starting method that avoids these inrush currents and mechanical overloading. ABB has successfully introduced a wide range of softstarters to the market.

A softstarter is a device, based on power electronics, that controls the voltage input to a motor starting up and thereby reduces the initial torque and current, which may be multiples of the rated values → 5.

At the heart of a softstarter are thyristors. These bipolar semiconductors – conceived in the 1950s – are now available for very high voltage and current ratings. The thyristors in a softstarter are connected back-to-back on each motor voltage input line and their firing angle adjusted to control startup voltage. Gradually, the firing angle is varied to allow voltage and torque to increase and speed up the motor.

One of the benefits of using a softstarter is that the torque can be set to the exact value required – this torque control feature is an important competitive differentiator.

Another important feature of the softstarter is its soft stop function. This is very useful for stopping pumps in water systems prone to exhibit water hammer when a direct stop using a star-delta starter or direct-on-line starter is employed. The soft stop function can also be used to avoid any material damage

Gradually, the thyristor firing angle is varied to allow voltage and torque to increase and speed up the motor.

that might be caused by abruptly stopping a conveyor belt.

ABB softstarters

After much pioneering work by themselves and others during the 1970s, Fairford Electronics in England became one of the first companies to design and produce a three-phase motor controller with automatic energy optimization – with the added functionality of being able to soft start the motor to save energy. By 1982, ASEA had noticed the idea and instigated a collaboration with a small Swedish company, Elfi, to use components from Fairford Electronics along with Elfi know-how to develop an ASEA softstarter.

The project was a success and ASEA's first softstarter – called DEHE – was launched at the Elfack exhibition in 1984. At the time, few were aware of the benefits of a softstarter, so ASEA had the additional task of educating the market. Initial sales were mostly confined to

Swedish mining and paper customers.

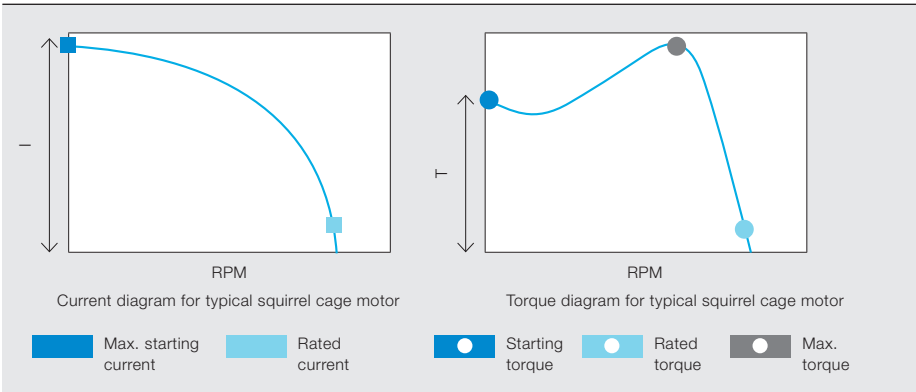
The basic components in a modern softstarter are mostly the same as in the early versions: A contactor, an over-

load relay and the inverse-parallel semiconductor devices (thyristors) → 6. Also, there is a printed circuit board, a heat sink, fans and housing.

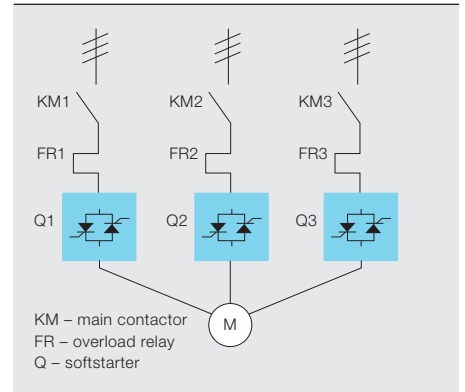
By 1993, a new version – the PSD – with extra functionality was introduced. Being available for a range of voltages, it opened up new markets around the world. The PSD was successful all through the 1990s and although Fairford Electronics was still responsible for the technical aspects, ABB took advantage of its strong market organization and experience to sell the product widely.

The first ABB softstarter, type PSS, appeared in 2000, designed and built in a custom factory in Örjan, just outside Västerås, in Sweden. Two years later, the product was further improved and the product range was divided into low-end (the PSS) and high-end (the PSD) products.

5 Induction motor current and torque – without a softstarter, initial values can be a multiple of rated values.



6 Softstarter – simplified schematic



7 ABB's softstarter range



ASEA's first softstarter – called DEHE – was launched at the Elfack exhibition in 1984.

In 2004, a new version – the PST – was launched, helping ABB become the market leader in softstarters, especially in China. The PST was the first softstarter to have a built-in bypass for normal operation, which saves energy by avoiding thyristor conduction losses. Subsequent development work concentrated on new algorithms to enhance the product's functionality, and the use of modeling and simulation tools to investigate the operation of the softstarter when applied to water pumps. Cost reduction was also a focus area and, in 2010, when the PSE

was released, ABB had established clear all-around leadership in softstarters.

By 2014, the importance of device communication had been recognized and many of today's softstarters are equipped with a port for such communication, which is normally carried out over fiber optic cables → 7. Many different communication protocols are supported – for example, Modbus, PROFIBUS, DeviceNet, Interbus-S, LonWorks, etc. Further, it has become clear that diagnostics, the human-machine interface (HMI) and the integration of softstarters with other devices – such as programmable logic controllers (PLCs) – are also key features. All these considerations were taken into account in the PSTX – ABB's brand-new softstarter.

As with many other industry devices, the need for diagnostics will increase in the future as reliability and availability become more important. New disruptive technologies, like the Internet of Things, Services and People (IoTSP), are clearly leading the trend for connectivity at a

higher level that will allow better preventive maintenance and integration with the factory environment.

Hector Zelaya De La Parra
 ABB Corporate Research
 Västerås, Sweden
 hector.zelaya@se.abb.com

Maria Widman
 ABB Electrification Products,
 Protection and Connection
 Västerås, Sweden
 maria.widman@se.abb.com

Sören Kling
 ABB Electrification Products,
 Sales & Marketing
 Västerås, Sweden
 soeren.kling@se.abb.com

Gunnar Johansson
 ABB Electrification Products,
 Protection and Connection
 Västerås, Sweden
 gunnar.c.johansson@se.abb.com

Driving ideas

The leading edge of motor development

FREDDY GYLLENSTEN, DMITRY SVECHKARENKO, REZA RAJABI MOGHADDAM – ABB has developed a revolutionary technology called the synchronous reluctance motor – or SynRM, for short. The design of SynRM electric motors makes them inherently reliable, highly efficient and able to pack high power levels into a small volume.

The induction motor (IM) dominates industrial applications, even in variable-speed applications such as the water pumping illustrated in → 8. This is because an IM will start directly on the grid – historically the way of starting and one that continues to this day, even after the introduction of modern frequency converters. However, the IM has some inherent drawbacks as a result of its asynchronous operation that result in relatively high rotor losses, and heating of bearings and windings that impacts maintenance intervals and shortens the lifetime of bearings and insulation.

The synchronous reluctance motor does not have these drawbacks and is much better suited to variable-speed operation.

SynRM motor technology

Although long known, permanent magnet AC motors only became competitors to IMs in the 1980s with the creation of a new generation of permanent magnets based on rare-earth elements (REEs). A prerequisite for the introduction of these new magnets into motors was the parallel advancement of the AC drives that were needed to control and operate the motors.

The drawbacks of an IM are absent in a synchronous reluctance motor and it is much better suited to variable-speed operation.

However, REEs are costly and can be subject to price variations. Also, their strong magnetic rotor field can make servicing – a key feature of a mainstream industrial motor – more difficult. Enter the REE-free synchronous reluctance motor.

The synchronous reluctance motor is a three-phase electric motor with a magnetically anisotropic rotor structure comprised of stacked electrical steel plates with punched holes as flux barriers. In the four-pole version, the rotor has four high-permeance and four low-permeance axes. High permeance means high magnetic conductivity and higher inductance while low permeance means lower inductance. Reluctance is the inverse of permeance and is, in practical terms, magnetic resistance; high reluctance

results in low inductance. The axes with high permeance (iron) can be referred to as the direct or d-axis while the axes with high reluctance (air) can be referred to as the quadrature or q-axis → 9.

When a magnetic field is produced in the air gap by applying excitation currents to the stator windings, the rotor will strive to align its most magnetically conductive axis, the d-axis, with the applied field, in order to minimize the reluctance in the magnetic circuit. In other words, torque is produced in the air gap between the stator and rotor whenever the applied field vector and the d-axis of the rotor are not aligned. This causes the rotor to rotate. The rotor runs in synchronism with the applied magnetic field, striving to minimize reluctance in the magnetic circuit. This functional principle has given its name to the technology – synchronous reluctance.

As the rotor has no windings and, consequently, no joule losses, it runs considerably cooler and with better efficiency and reliability than an IM. Synchronous reluctance motors run smoothly due to the sinusoidal air gap field distribution and operation with sinusoidal current. One drawback is that the motor cannot be started with a direct-on-line supply as the rotor position must be known.

8 Industrial LV motors pumping water

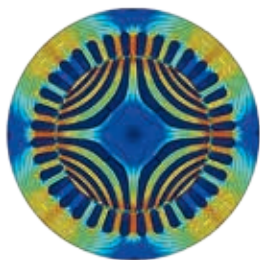


ABB's involvement in SynRM took off in 2004.

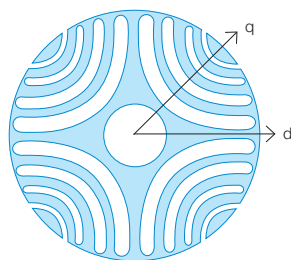
which can start directly on the grid since it is equipped with a squirrel cage inside the SynRM rotor barriers.

SynRM has come a long way since its early days but is still a relatively young technology for commercial use. Current ABB products have the potential to improve their performance even more with updated designs and constructions, and thus offer optimized solutions for customer needs many and varied.

9 Four-pole synchronous reluctance motor



9a Cross-section of a four-pole synchronous reluctance motor



9b Definition of the magnetic d- and q-axes of the rotor



9c Motor assembly

History of SynRM motor development

ABB's involvement in SynRM took off in 2004 when new opportunities for synchronous reluctance motors in the thriving VSD-based market were identified. The technology would enable higher efficiency and reliability without the need for REE permanent magnets. The favorable results of initial explorations eventually led to a technology project starting in 2007. At the same time, the market appetite for the product was tested.

To deepen understanding, an MSc activity on the motor concept was initiated in 2006. This work was subsequently continued into a PhD.

By 2009, good technical progress had been made – for example, bearing failure and rotor sheet failure had led to comprehensive durability testing and failure mode analysis – and in 2011, develop-

ment was far enough advanced to unveil SynRM at the Hannover Fair. In that same year, the technology won the Automation Award at Germany's SPS IPC Drives trade show. The first products were launched in 2012.

An expansion to the SynRM product palette – SynRM2 – was introduced in 2014. A unique feature of this motor – mainly developed by ABB's key SynRM contributors Alessandro Castagnini, Pietro Savio Termini and Giulio Secondo – is that it uses ferrite (Fe_2O_3) magnets, which are generally more cost-effective and more readily available than REE magnets. This results in a very powerful product that is economical and ecologically sustainable.

The following year, 2015, the SynRM family was extended once more with the technology introduction of DOL SynRM,

Freddy Gyllensten

Dmitry Svechkarenko

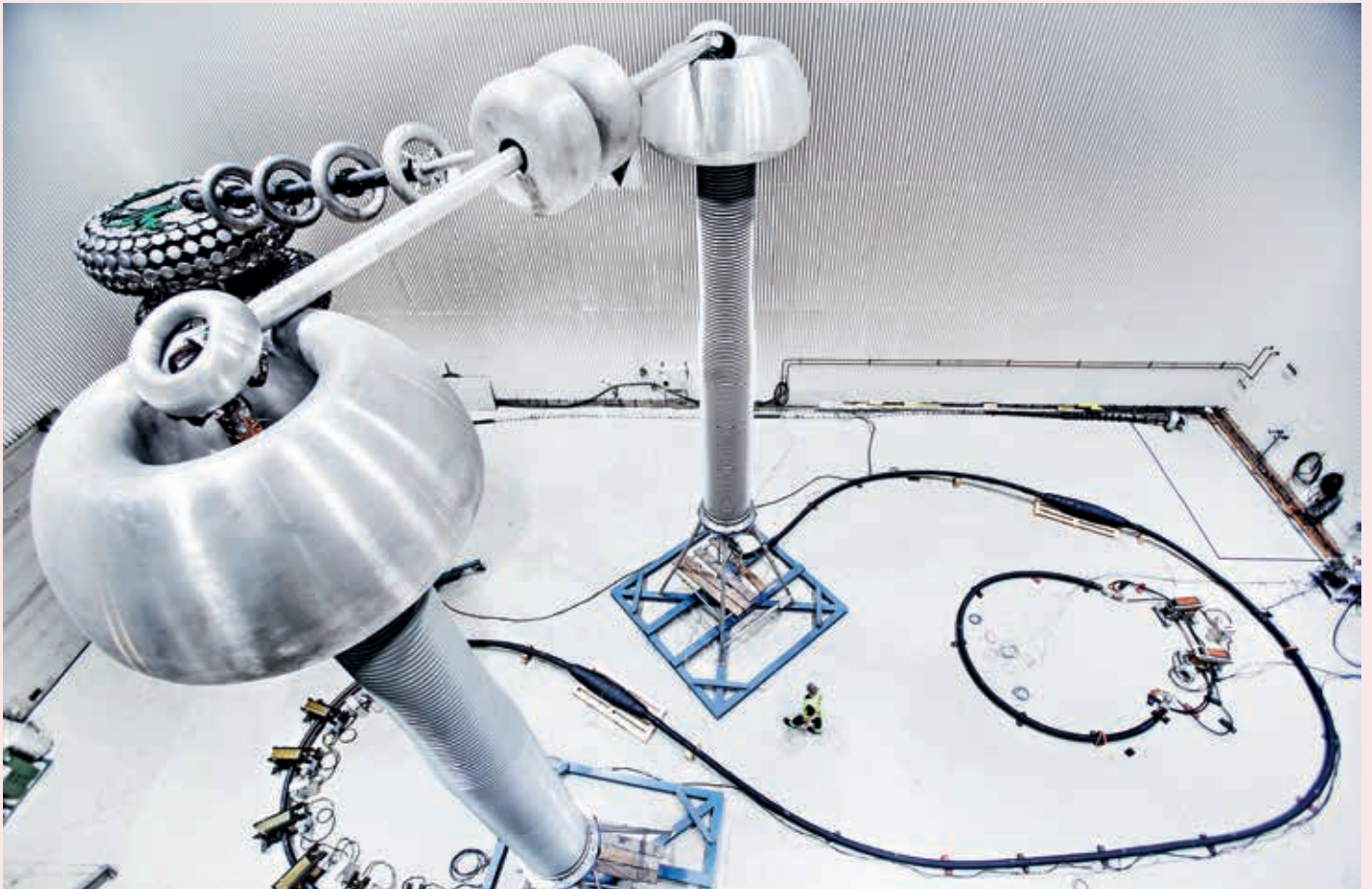
Reza Rajabi Moghaddam

ABB Discrete Automation and Motion,
Motors and Generators
Västerås, Sweden

freddy.gyllensten@se.abb.com

dmitry.svechkarenko@se.abb.com

reza.r.moghaddam@se.abb.com



A direct link

HVDC technology for better power transmission

Modern society has evolved in a way that demands large quantities of electrical power be transferred across regions and continents. For this, high-voltage direct current (HVDC) power lines are ideal. Apart from the higher efficiency of HVDC, the capabilities of modern power electronics have simplified the technology, with the result that the infrastructure it requires is less complex, less bulky and more amenable for inclusion in concepts like smart grids than is the case for high-voltage alternating current (HVAC).

Title picture

Ever more HVDC links are being installed worldwide to move large amounts of electrical power efficiently. Shown is a 525 kV extruded HVDC cable system under test.

After being vanquished in the field of power transmission and distribution by AC technology in the early 20th century, DC technology had to wait until the 1950s and the advent of capable converter technologies to make its resurgence.

Early on, DC had lost ground to AC because DC posed various challenges – such as how to step voltages up and down, a task relatively simple in the AC world. However, DC is a far superior way to transmit power as operating at high voltages – and thus low currents – is more efficient.

Over the decades, HVDC has been used for submarine transmission and back-to-back connections, but the technology needed for it was electromechanical and cumbersome. Only with the advent of power electronic components such as insulated-gate bipolar transistors (IGBTs) did compact HVDC systems become economically and practically feasible. ABB's product in the voltage source converter (VSC) HVDC field is called HVDC Light®.

An HVDC Light system is not just one single product; a range of innovative products and solutions are needed to implement HVDC – such as appropriate cables, breakers and the sophisticated power electronics at the core of the system.

A direct link

Efficient power transfer with HVDC Light®

JAN R. SVENSSON – Modern day ABB HVDC activity can be traced back to a 1993 study by Gunnar Asplund, HVDC research manager, on utilizing VSCs for HVDC. In the intervening years, ever-larger and more sophisticated HVDC links have been installed around the world and HVDC has turned into a billion-dollar business for ABB.

On the basis of the positive results of Asplund's study, ABB initiated, in August 1994, a large project to further explore the VSC approach.

The IGBT was the workhorse of the new technology. IGBTs are metal-oxide semiconductor (MOS) devices in which the power needed for the control of the component is very low and can be taken from the snubber circuit connected in parallel. Therefore, no auxiliary power from ground level is needed to power the gate unit (GU). Moreover, both the turn-on and turn-off switching of the IGBT can be controlled precisely by the GU, which makes it possible to connect the IGBTs in series.

The key technology developed by ABB was the series connection of IGBT press-packs to handle high voltages, together with the development of a short-circuit failure mode (SCFM) concept and appropriate testing regime.

To successfully handle series-connected IGBTs, they all need to be switched (on

or off) at the same time so each IGBT experiences the same voltage stress. For a VSC HVDC station, this means hundreds of IGBTs have to be switched individually in a fraction of a microsecond.

A complete series-connection concept was developed, including design, manufacturing and tuning of the GUs together with the snubber circuits and the power

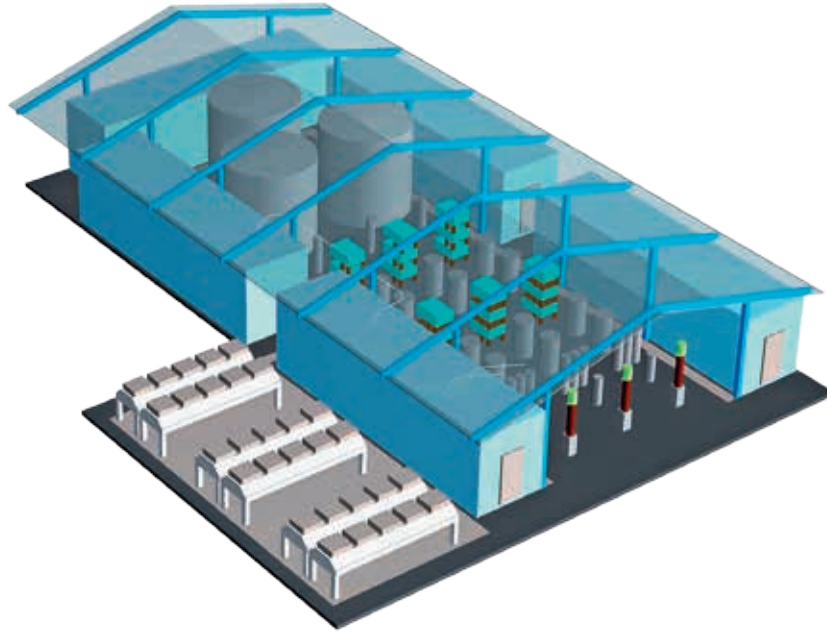
A key technology developed by ABB was the series connection of IGBT press-packs to handle high voltages.

supply. Finally, the concept was verified by building an H-bridge prototype with four series-connected IGBTs per valve.

The feasibility of the VSC HVDC concept was shown in 1997 by a demonstrator installed between Hällsjön and Grängesberg, in central Sweden, on a 10 km, temporarily decommissioned 50 kV AC line. The demonstrator specifications were:

- Rating of 3 MW / ±10 kV, switching frequency 1,950 Hz
- Two stations utilizing two-level, three-phase VSCs

1 Gotland HVDC Light project.



- 2.5 kV/250 A press-pack IGBT
- IGBTs cooled with deionized water
- Mix of overhead line and cable
- DC breaker and DC chopper utilizing series-connected IGBTs

On March 10, 1997, power was transmitted on the world's first VSC HVDC. An extensive test program followed, showing that the concept fulfilled all the expectations.

Introduction of HVDC Light

In May 1997, ABB launched HVDC Light and customers were invited to Sweden for seminars and a study visit to the demonstrator. The HVDC Light design was based on a modular concept with a number of standardized sizes in the range of 10 to 100 MW. The design had two-level converters up to around ± 80 kV.

HVDC Light was launched as an environmentally friendly product: Since power is transmitted via a pair of underground cables there is no visual impact. The balanced voltage to ground eliminates the need for an electrode so there is no ground current and no electromagnetic field emanates from the cable pair.

The stations are designed to be unmanned and are, in principle, maintenance-free. Operations can be carried

out remotely. The first pilot installation of HVDC Light started operation in November 1999 on the Swedish island of Gotland with two extruded 80 kV cables with a total length of 140 km connecting the terminal stations → 1.

Applications

As a synchronous generator, the VSC creates its own phase voltages. A cascaded controller achieves fast control of the active and reactive currents independently of each other in an inner controller, while the outer, slower, controller tracks either the active power reference or the DC link voltage reference, utilizing the active current. The reactive current is used to control the AC voltage or inject/consume reactive power. The cascaded controller together with outer control loops allow a wide variety of application areas to be served, for example:

- Interconnecting grids.
- The connection of generation assets remote from the consumer – eg, offshore wind – and supply of remote loads, eg, power from shore to oil and gas platforms.
- DC links in AC grids enhance the AC grid performance. HVDC Light removes bottlenecks in existing AC grids and eases right-of-way for cable lines. Moreover, HVDC Light improves

For a VSC HVDC station, hundreds of IGBTs have to be switched individually in a fraction of a microsecond.

The feasibility of the VSC HVDC concept was shown in 1997 by a 10 km, 3 MW / ± 10 kV demonstrator installed in central Sweden

2 Troll A platform. The HVDC Light station is the gray box between the cranes.



- AC grid stability and reliability levels and increases power quality.
- City-center infeed. HVDC Light has a small footprint and its cable technology eases right-of-way on existing routes.

Higher voltages and powers

To meet customer demand for higher powers and lower losses, HVDC power semiconductors and their packaging have undergone continuous development. This has enabled optimization of converter topologies and control algorithms, including pulse-width modulation (PWM) strategies.

HVDC Light: 2002 – 2005

A new generation of extruded polymer insulated cable was created to enable a DC link voltage of ± 150 kV. A converter station using a three-level active neutral point clamped VSC was also developed. These were utilized in two projects: the 330 MW Cross Sound Cable Project and the 220 MW Murray Link. The station separation in the latter is 180 km.

HVDC Light: 2005 – 2007

In a further development, a new generation of semiconductors made it possible to go back to the two-level converter topology by using an optimized PWM algorithm. A number of projects were delivered, including the 300 MW Caprivi link, which was the first HVDC Light with an overhead link to connect the northeastern and central parts of Namibia (950 km).

HVDC Light: 2007 –

The latest HVDC Light delivers increased power at lower losses by utilizing a modular multilevel converter (MMC) topology with half-bridge converter cells. This technical advance has enabled projects such as the 800 MW DoWin1, which is the first HVDC Light project that uses 320 kV extruded cables; and the 1,400 MW North Sea Link, which is a bipolar HVDC Light connection between Norway and the United Kingdom (730 km). It will be commissioned in 2021.

Drive systems using HVDC Light on an offshore platform

Many offshore applications are ideal candidates for HVDC. The Troll A gas platform in the North Sea, for example, uses compressors to boost gas pressure in the pipelines, which deliver gas to the mainland, 70 km away. Usually, the platform generator required to power compressors is bulky and not particularly efficient. However, ABB had been working on very-high-voltage (VHV) electrical motors based on stator windings that exploit extruded AC cables with polymer insulation. A VHV motor can be connected directly to HVDC Light without using a transformer. Utilizing power from the mainland via VHV motor and HVDC Light confers many advantages:

- Electricity from the mainland is generated with less greenhouse gas emission
- Higher efficiency and less maintenance than gas turbines or diesel engines

- Reduced weight and space requirements on the platform

In 2005, two parallel systems were installed in Troll A – ± 60 kV with a VHV motor of 44 MW/56 kV AC. Two further systems were completed in 2015 with a VHV 50 MW motor power and voltage of 66 kV AC → 2.

The future is HVDC Light

In just 19 years, the visionary 3 MW demonstrator has multiplied to 25 HVDC Light installations that transfer over 10 GW and a worldwide billion-dollar ABB business has grown. The rapid development of HVDC Light will continue due to drivers such as climate change, the addition of renewables to the grid, demand for better power quality and the close integration of energy markets with the power infrastructure.

The attractiveness of HVDC Light will continue to grow as technology pushes powers ever higher and losses lower with the introduction of new semiconductors, new materials for cables and new high-voltage converters.

Jan R. Svensson

ABB Corporate Research
Västerås, Sweden
jan.r.svensson@se.abb.com

A direct link

Ultrafast disconnecter for hybrid HVDC circuit breaker

LARS LILJESTRAND, JÜRGEN HÄFNER – An ultrafast disconnecter is a key component of ABB's new hybrid HVDC circuit breaker. The story of the hybrid HVDC circuit breaker development is a textbook example of the strengths of power electronics.

Any electrical system has to be able to handle faults by disconnecting the fault and isolating just as much of the power system as it needs to. With today's HVDC point-to-point transmission lines, AC breakers at each end can take up this task → 3. However, HVDC systems will increasingly be configured in grids and using the AC breakers to clear faults would cause the loss of the entire grid → 4. Further, HVDC faults have to be cleared in a few milliseconds, much faster than in a corresponding AC system.

In other words, an HVDC breaker is needed.

Hybrid DC circuit breaker

Until recently, no DC breaker has proven suitable for HVDC due to HVDC's high voltage, high and fast-rising short-circuit current, and requirement for fast current interruption. This was ABB's motivation to develop a new type of breaker – the hybrid DC circuit breaker. This innovative breaker combines the low losses of a mechanical switch with the superior current interrupting capabilities of a power

electronic switch and fulfills the requirements of fast interruption of short-circuit currents in HVDC grids.

The new breaker consists of a main breaker branch comprising power electronic switches and surge arresters, and a parallel branch containing an ultrafast disconnecter (UFD) and

abled by a contact system of parallel- and series-connected contacts.

The parallel-connected contacts permit high nominal currents when the switch is closed; the series-connected contact enables a high voltage to be withstood when the switch is open → 6–7. The short actuator stroke of the series-connected

contact allows fast opening while ensuring high mechanical endurance. The actuators are of the Thomson type and move in opposite directions to double contact separation speed. The switch is installed in pressurized gas to improve the voltage withstand.

The unique requirements placed on the mechanical switch could not be fulfilled by previously available switches, making the UFD a key component of the hybrid circuit breaker.

a power electronic load commutating switch → 5. The unique requirements placed on the mechanical switch could not be fulfilled by previously available switches, making the UFD a key component of the hybrid circuit breaker.

The ultrafast disconnecter

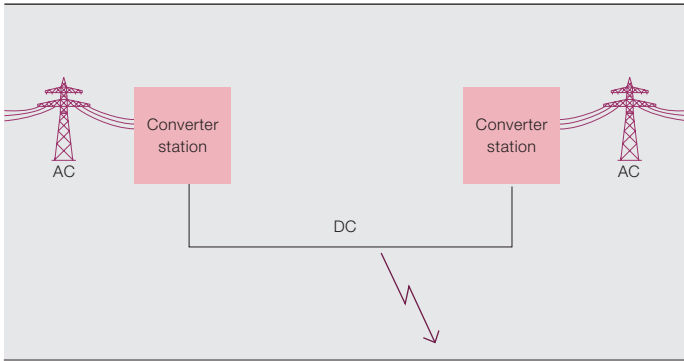
The ultrafast disconnecter is a very fast mechanical switch able to carry high nominal current with negligible losses. After opening, it should be capable of withstanding a high voltage within a few milliseconds. This functionality is en-

History of the UFD: 2000–2002

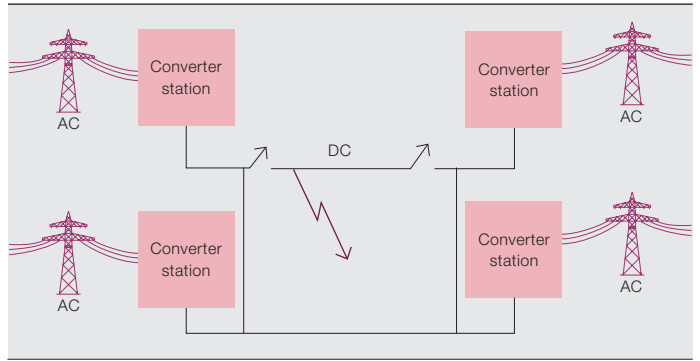
The need for a fast commutating switch for bypassing power electronic switches was identified in 1999 and a project was started in 2000 to build a demonstrator aimed at medium-voltage (MV) fault current limiter applications. The initial design used rotary contacts and was successful so a full project was promptly started, which, within the year, led to an improved linear contact design.

In 2002, the technology development was finished for the 17.5 kV MV application.

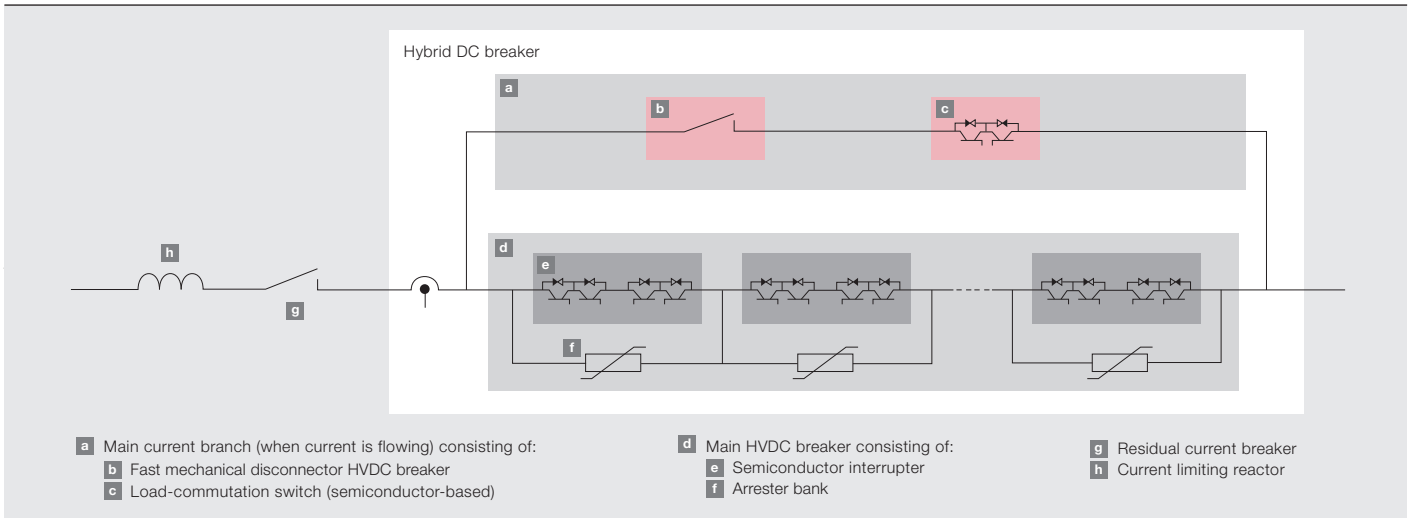
3 AC breakers can be used to disconnect a fault in a point-to-point HVDC line.



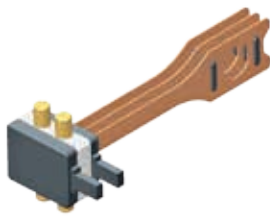
4 Using a breaker in the AC section of the power system to clear a fault in an HVDC grid would disable the entire grid.



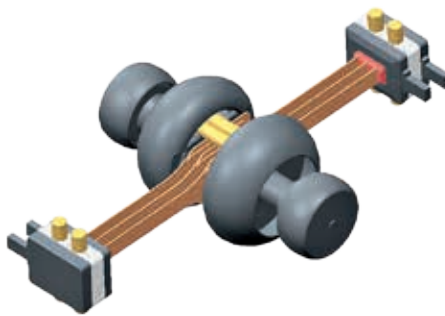
5 Hybrid HVDC breaker



6 Parallel-connected contacts in the UFD



7 Series-connected contacts in the UFD



17.5kV to 320kV. Other concepts were also evaluated and compared. As history shows, the commutating switch based on series and parallel connection of mechanical contacts was found to fulfill the requirements and be the most suitable for the application. Productization was started in 2011 in Switzerland.

The development work initiated in 1999 is still bearing fruit and it is to be expected that power electronic switches in combination with a parallel mechanical bypass switch are destined to find use in a host of other electrical applications.

The development work initiated in 1999 is still bearing fruit.

UFD: 2010 – present

By 2010, HVDC grids were being discussed, but a breaker appropriate to the demands of HVDC did not exist. A hybrid DC circuit breaker was proposed, but the UFD it needed was missing. Those familiar with the fast commutating switch work from 10 years previously proposed that approach for a UFD development.

A project was started to see if the previous concept could be scaled up from

Lars Liljestrand
 ABB Corporate Research
 Västerås, Sweden
 lars.liljestrand@se.abb.com

Jurgen Häfner
 ABB Power Grids, Grid Systems
 Ludvika, Sweden
 jurgen.hafner@se.abb.com

A direct link

Sophisticated HVDC extruded cable technology

CARL-OLOF OLSSON – Advanced HVDC systems need advanced cables. XLPE cables are providing the foundation for sophisticated HVDC power transmission technology.

At the end of the 1940s, the first extruded power cables appeared. Polyethylene was chosen as an insulator for these cables – primarily because it had low permittivity, suitable mechanical properties and high thermal conductivity. About 10 years later, the technology to cross-link polyethylene was established and XLPE insulation became the most popular choice for high-voltage cables, and so it has remained.

For submarine HVDC cables, mass-impregnated (MI) insulation or XLPE can be used. For land cables, XLPE is preferred due to the lower total weight and the simpler jointing.

Insulation system improvements

With the first power cables, a century-and-a-half ago, the insulation layer was applied directly onto the conductor. How-

XLPE insulation became the most popular choice for high-voltage cables, and so it has remained.

ever, it was soon discovered that a significant increase in the operating voltage could be obtained when a metallized paper was placed around the conductor to smooth out localized electric field effects. Cable development continued apace and a major advance came in the late 1960s with XLPE cables produced in a triple-extrusion process in which the insulation layer was extruded together with an inner and outer semiconducting polymer layer.

In 1997, ABB introduced extruded direct current cable systems. Improvements in the dielectric properties of the XLPE have enabled higher voltages – starting at 80 kV and now reaching 525 kV → 8. The total cost of cable systems is continuously decreasing thanks to improved efficiency in the manufacturing processes and installation.

HVDC cables for high power over long distance

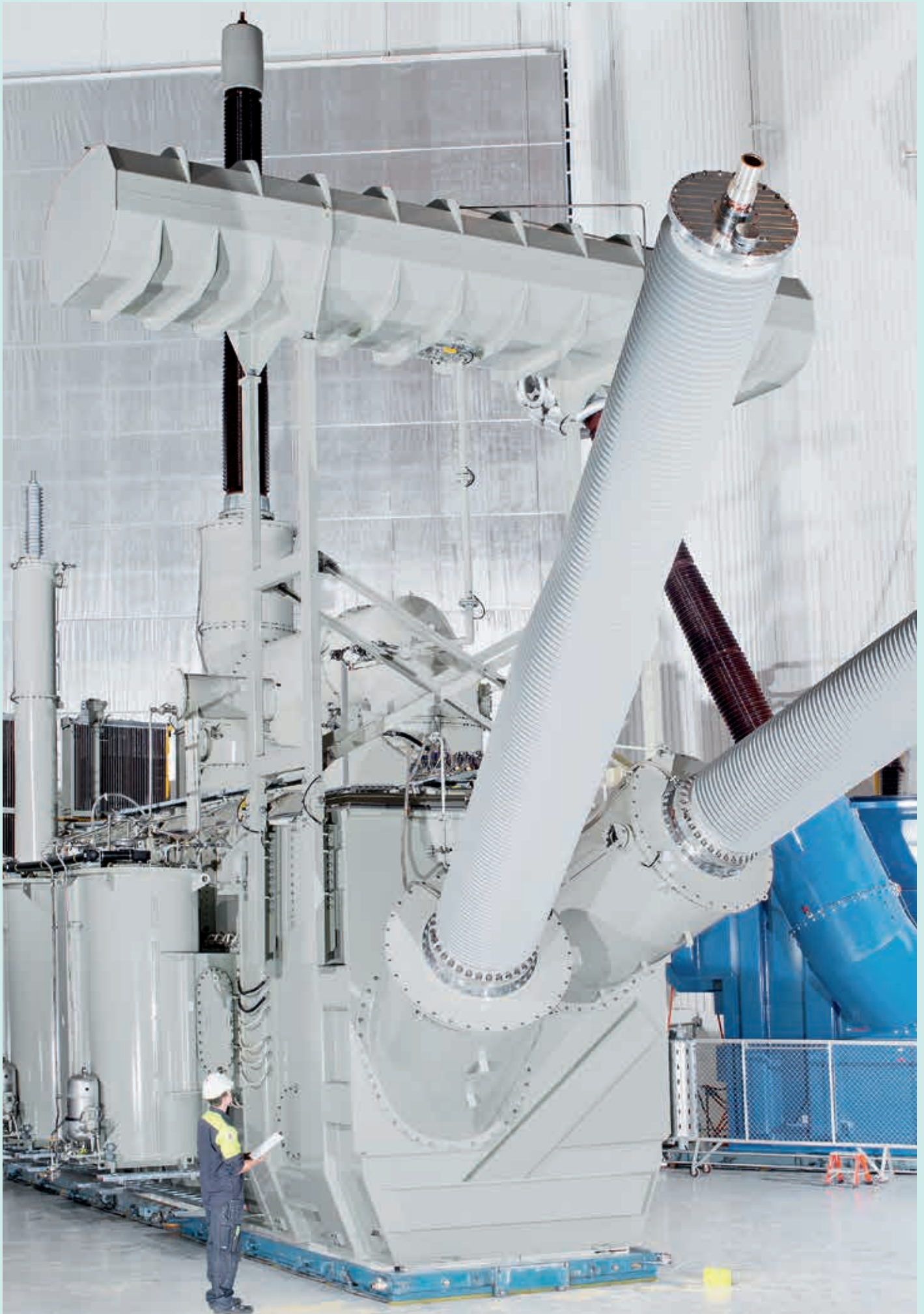
The maximum voltage level for ABB's newest XLPE insulated cables is 525 kV. To make this possible, an insulation grade providing lower electrical conductivity is used, and special joints and terminations have been developed. Qualification testing was performed at a 70 °C conductor temperature (MI cables have a maximum operating temperature of 55 °C). Future research and development will most likely make higher operating temperatures and voltage levels possible.

New investments in cable systems will enable the use of energy in a more environmentally friendly and sustainable way.

8 Modern XLPE cables have a sophisticated layer structure that can be customized according to the application, but remains flexible.



Carl-Olof Olsson
ABB Corporate Research
Västerås, Sweden
carl-olof.olsson@se.abb.com



Transforming and changing

Transformer insulation science and innovative tap changers for high-power applications

As power levels in the electrical transmission grid continue to rise – into multiple-GW territory – more demands are placed on the transformers that enable the transfer of these huge quantities of energy. At the extreme, in the ultrahigh-voltage direct current (UHVDC) range, traditional insulation approaches are no longer appropriate, so fundamental research is required – for example, to explore and mitigate the disruption caused by ion drift effects at high voltages. Equally, new concepts have to be devised for on-load tap changers to avoid deterioration of the insulation oil that would otherwise occur using traditional switching methods at these high voltage levels.

UHVDC technology provides the most efficient way to transfer bulk energy over long distances. The very first ABB installation of this kind was the Gotland Link, in Sweden, in 1954. A major advance was made when the voltage rating was raised from 400 kV DC to ± 600 kV DC in 1984, for the Itaipu project in Brazil – an installation that remained the world's highest HVDC transmission voltage rating for more than 25 years. In 2010, a ± 800 kV DC line was installed in China and only two years later a new world record was set by the converter transformer prototype for 1,100 kV DC in Ludvika, Sweden.

With BBC's first oil-filled transformer being built in 1893 and over a century of transformer development since, ABB has the experience necessary to undertake such projects. In recent years, the challenges arising from high-voltage direct current (HVDC) and UHVDC transmission have triggered new advances in basic science and technology that have further enhanced ABB's position in this field. For example, a scientific understanding of physical phenomena such as ion dynamics in the oil/cellulose insulation system of converter transformers has significantly contributed to ABB's technical leadership when it comes to HVDC and UHVDC converter transformers.

Switching high voltages poses a challenge, especially when the winding ratios are changed on an energized power transformer using an on-load tap changer (OLTC). The OLTC is designed to handle the electrical power that arises when the

current in one regulation step is broken and another is engaged. In a traditional OLTC, this switching process is done using transformer oil as the breaking medium. This creates arcs that, in the long run, will wear down the contacts and the insulating properties of the oil.

ABB has developed a new product range of OLTCs based on vacuum interrupter technology. In this approach, the electrical arcs created during the switching operation are confined to the vacuum interrupter. This prevents oil degradation and increases contact lifetime (up to 1,000,000 operations). Another advantage is the high current interruption capability of vacuum interrupters, which allows OLTCs to be built that have higher power ratings than the equivalent traditional type.

Title picture

What are some of the challenges faced by designers when transformers are expected to work at very high voltage levels?

Transforming and changing

Vacuum-based OLTCs

LARS JONSSON, MAGNUS BACKMAN, PETER NILSSON – ABB has developed a new product range of on-load tap changers (OLTCs) based on vacuum interrupter technology. The new OLTCs confine arcs to a vacuum interrupter, thus avoiding the transformer oil degradation and contact wear that traditional OLTCs experience.

Traditionally, when winding ratios are changed on an energized power transformer using an OLTC, arcing occurs in the transformer oil. Over time, these arcs will degrade both the OLTC contacts and the insulating properties of the oil, necessitating regular services and oil changes.

Advantages of vacuum interrupter technology

ABB's new OLTCs confine the arcs within a specially developed vacuum interrupter. This eliminates oil degradation and increases contact lifetime (to 1,000,000 operations). Further, OLTCs that utilize vacuum interrupters have a much higher current interruption capability than the equivalent traditional type.

History of vacuum interrupter OLTC development

OLTCs and vacuum switches existed in parallel from the early 1900s before they were combined into a single product. In the 1970s, ASEA patented various aspects of vacuum interrupter technology, including OLTC applications. At first, the combination of OLTC and vacuum switches was made on the reactance-type tap changers that was, and predominantly still is, used in the United States, operating on the low-voltage side of the transformer at high currents.

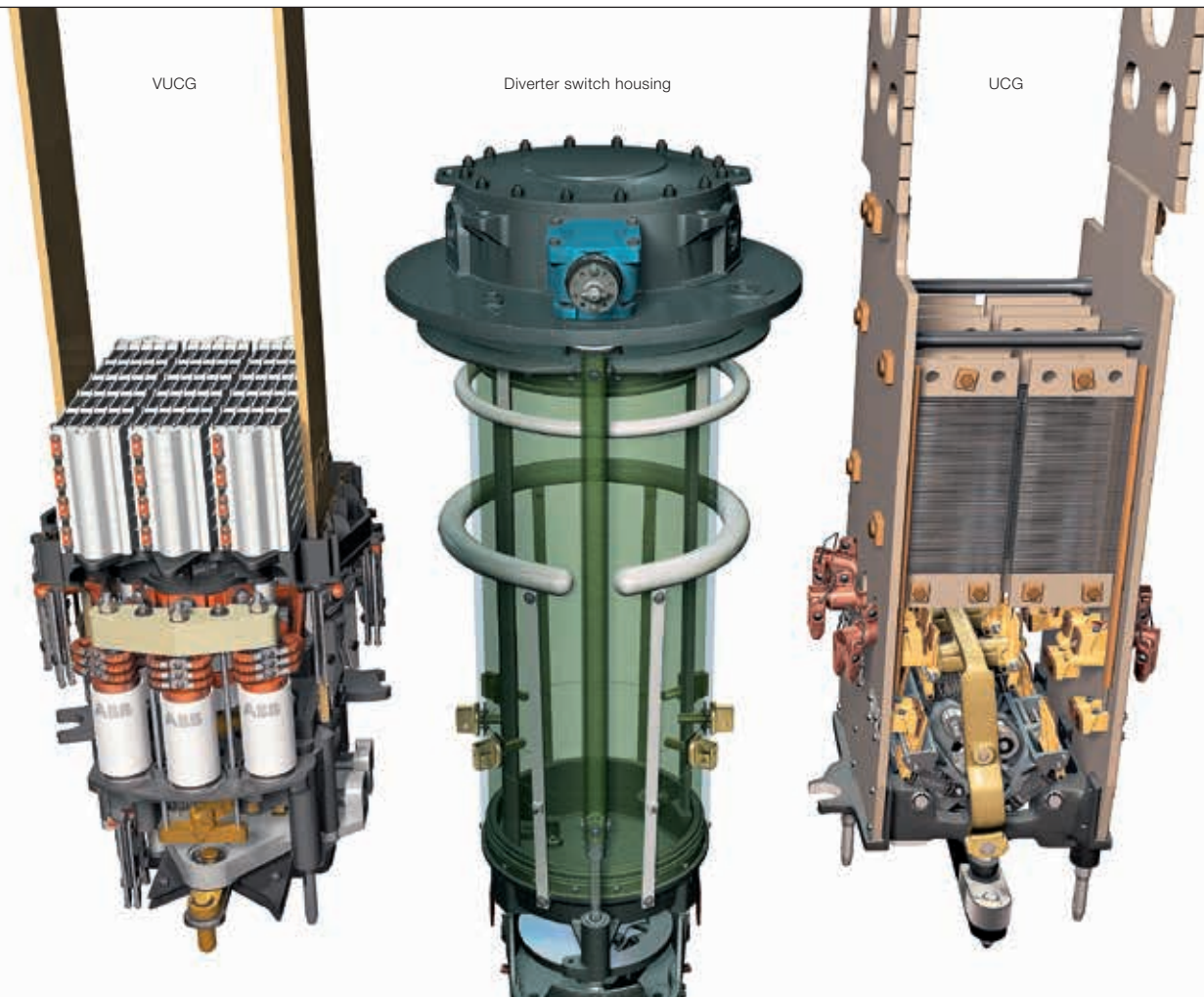
However, the technology only took on major significance with the later deregulation of the energy sector in many countries and the resultant drive to improve asset utilization, reduce service requirements and increase equipment lifetime.

To meet these new demands, ABB Corporate Research in Sweden carried out a prestudy in 2002 to assess OLTCs based

ABB's new OLTCs confine the arcs within a specially developed vacuum interrupter. This eliminates oil degradation and increases contact lifetime.

on vacuum interrupter technology. This led, in the following year, to a project group being formed and the first sketches for the VUCG design. The VUCG integrates vacuum interrupters as well as auxiliary contacts operated with a unidi-

1 Diverter switch interchangeability makes field upgrade from traditional UC type tap changers to the new VUC type easy.



rectional mechanism, which is the main differentiator from competitor solutions.

In 2004, the first VUCG diverter switch prototype was designed and built. 2005 saw the introduction of a new spring mechanism using compression springs, after previous solutions, which used clock springs, were shown to be insufficiently reliable. Also, a new mechanical rectifier to provide unidirectional rotation was designed. The VUCG was presented at CIGRE 2006.

In 2006, the first prototype of the new VUCL was designed and built. The design was similar to the VUCG but contained a switch to bypass the vacuum interrupters in normal operation – thereby allowing higher currents. The following year saw the initial design of the VUBB. Also, a selector switch type with compensation for the position of the cam slot was invented.

The VUCG that was introduced to the market in 2008 provides an easy field upgrade from traditional to vacuum technology → 1. The same year, development started on the optimization of the contact material for the vacuum interrupter. In 2009, the VUCG model reached 600,000 operations in an electrical endurance test. The following year, the first synthetic test circuit for vacuum tap changers was designed and built. This enabled long test series at high power.

In 2012, the VUCL and the VUBB were introduced to the market and in 2016, ABB introduced the world's most capable vacuum tap changer, VUCG 1800. The vacuum product range also includes the VRLTC, a reactor-type tap changer, developed by ABB for the United States market.

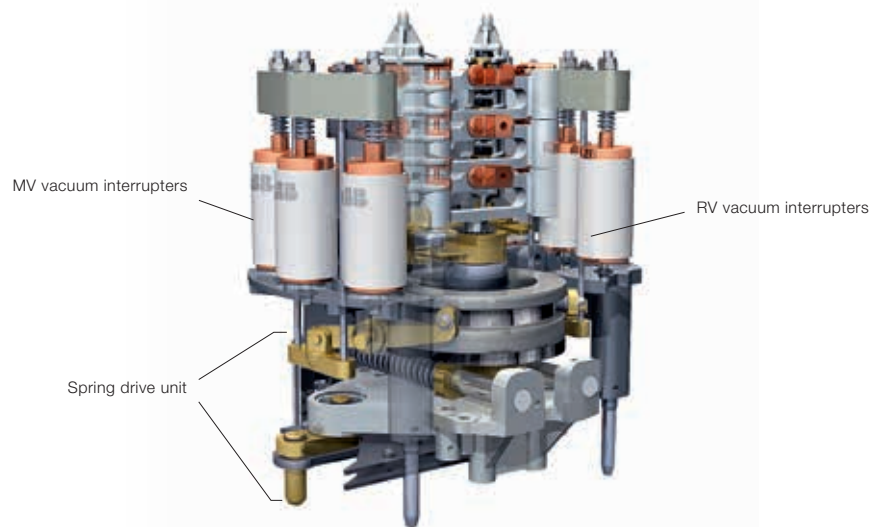
Functional description

The two key functions of the OLTC are to select the tap in a tapped winding and to commutate the load between taps in a

The VUCG that was introduced to the market in 2008 provides an easy field upgrade from traditional to vacuum technology.

Using vacuum interrupters in parallel for single-phase applications significantly reduces contact wear.

2 Diverter switch overview



tapped winding. Two fundamental design approaches are used in OLTCs:

- Selector switch type: Combines the selection, conducting and commutation of current in one compartment. The low number of parts used results in a highly compact design. This design has constraints that limit its use to transformers with ratings normally not exceeding 100 MVA/145 kV. VUBB is a selector switch type OLTC.
- Diverter switch type: Separates the load commutating device from the tap selector. It is used in a variety of applications and is the only type of tap changer suitable for high power/voltage applications. VUCG and VUCL are diverter switch type OLTCs.

In a diverter switch type OLTC, only the diverter switch, where the switching power is handled, uses vacuum interrupters. The tap selector part is identical to that of a traditional tap changer.

The diverter switch has two sets of vacuum contacts (MV, RV) and two sets of rotating auxiliary contacts → 2. The spring drive unit (SDU) converts the slow motion of the motor drive to the fast motion required for switching the contacts and also provides the synchronization required. The fact that energy is stored in springs ensures the switching cycle will be completed even if the power supply fails. Independent of whether the motor drive starts a raising or lowering maneuver, the

SDU will always be aligned in the same direction, ie, it is unidirectional. The unidirectional motion ensures that the contact switching sequence will be the same for all operations, giving a minimum switching stress on the electrical contacts.

The key component, the vacuum interrupter, is based on over 40 years of experience and millions of successfully delivered units, and is thus an extremely reliable product. However, in the unlikely event of vacuum interrupter failure, the auxiliary contact system is designed to carry out a certain number of tap operations by itself and trigger a protective relay alarm.

Introducing the world's strongest vacuum tap changer

ABB is continuing its 100-year history of pioneering tap changers with the introduction of the world's strongest tap changer, the VUCG 1800. The VUCG 1800 enables tap changing in high-end transformer applications without the need for enforced current splitting. The introduction of parallel breaking with vacuum interrupters is a leap forward in the application of vacuum technology. Using vacuum interrupters in parallel for single-phase applications significantly reduces contact wear on tap changers, even with high current levels and step voltages. The breaking current passes through three vacuum interrupters instead of just

one, which distributes wear more evenly over the contacts. The new tap changer uses the same proven vacuum interrupters as before, ensuring the same high quality and long service life as for all ABB vacuum tap changers.

Other switching techniques, eg, those based on semiconductors, will make another shift in technology possible. Semiconductor-based switching has already been applied in a pilot installation and, as in the case of vacuum technology, the time will come when it finds mainstream use in OLTCs.

Lars Jonsson

Magnus Backman

ABB Corporate Research

Västerås, Sweden

lars.e.jonsson@se.abb.com

magnus.backman@se.abb.com

Petter Nilsson

ABB Power Grids, Transformers

Ludvika, Sweden

petter.nilsson@se.abb.com

Transforming and changing

Fundamental research in UHVDC converter transformers

JOACHIM SCHIESSLING, OLOF HJORTSTAM, MATS BERGLUND – The converter transformer that connects the converter valve to the AC network is a key component of a UHVDC converter station. In order to design cost-effective and robust DC electrical insulation for this transformer, it is essential to obtain a deep understanding of the material itself as well as the physical processes that occur in the insulation under DC stress.

The main purpose of the converter transformer in an HVDC converter station is to transform the AC voltages from the AC network to the AC side of the converter valve. The electrical insulation of a converter transformer differs from that of a regular power transformer since it has to withstand combined AC and DC stress. Where the material parameter determining the AC field distribution is the permittivity, the DC field distribution is determined by the resistivity. Pressboard and oil differ by a factor of 2 in permittivity and by a factor of 100 in resistivity – thus more solid insulation is required for a converter transformer.

One major feature of DC behavior in the insulation material is that the governing parameter is not constant. Oil resistivity changes with applied electric stress,

Ion migration in DC fields leads to space charges at insulation interfaces that influence the electric field distribution significantly.

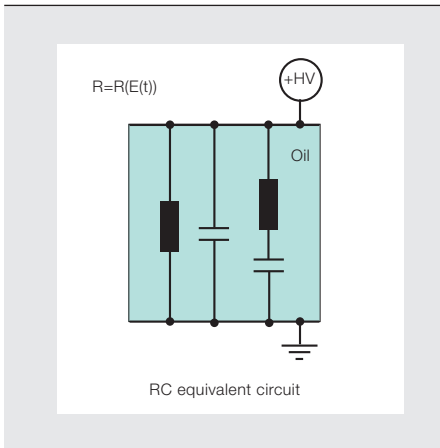
temperature, period of energization, moisture content, etc. Also, ion migration in DC fields leads to space charges at insulation interfaces that influence the electric field distribution significantly.

In order to design cost-effective and robust DC insulation, a deeper understanding of the physical processes under DC stress as well as material knowledge is vital. Typically, electrical insulation is designed using simplified calculations based on an equivalent RC circuit → 3. However, this cannot cover aspects such as space charge accumulation and the complex resistivity behavior of transformer oil.

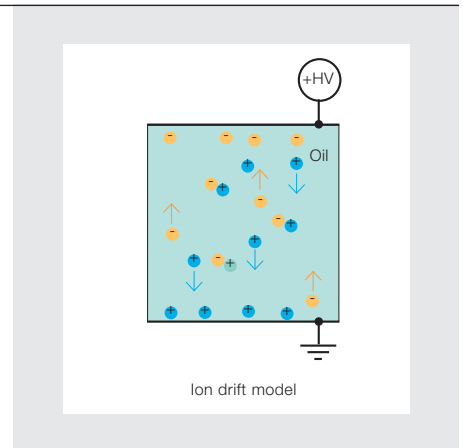
In the 1980s, the ASEA Research Center in Västerås investigated the DC properties of electrical insulation and developed a model that took ion generation and ion drift into account. The model was experimentally verified and implemented in a simulation tool. Thanks to this knowledge, unique technical solutions have been developed.

Nonlinear behavior of insulation liquids makes it difficult to use traditional resistive models to predict the electrical field distribution.

3 Two simulation methods for DC insulation systems



3a RC equivalent circuit



3b Ion drift model

4 The equations for the time-dependent ionic density in liquid insulation. These three-dimensional calculations require significant computer power to achieve good accuracy.

The ion-drift model

Continuity equations for concentration of positive (p) and negative (n) ions:

$$\frac{\partial p}{\partial t} + \nabla \cdot (\mu_p \bar{E} p - D_p \nabla p) = S$$

$$\frac{\partial n}{\partial t} - \nabla \cdot (\mu_n \bar{E} n - D_n \nabla n) = S$$

with μ_n, μ_p, D_n and D_p being the electrical mobility and diffusion constants for positive and negative ions.

Source term including generation and recombination of ions:

$$S = K_D^0 c F(E) - K_R p n$$

with $F(E)$ providing the Onsager field dependent contribution to the ion generation rate.

Poisson's equation including space charges (p-n):

$$\nabla \cdot (\epsilon_o \epsilon_r \bar{E}) = q(p - n)$$

with ϵ_o and ϵ_r being the dielectric constant and the relative dielectric constant.

The ion drift model for oil/cellulose insulation

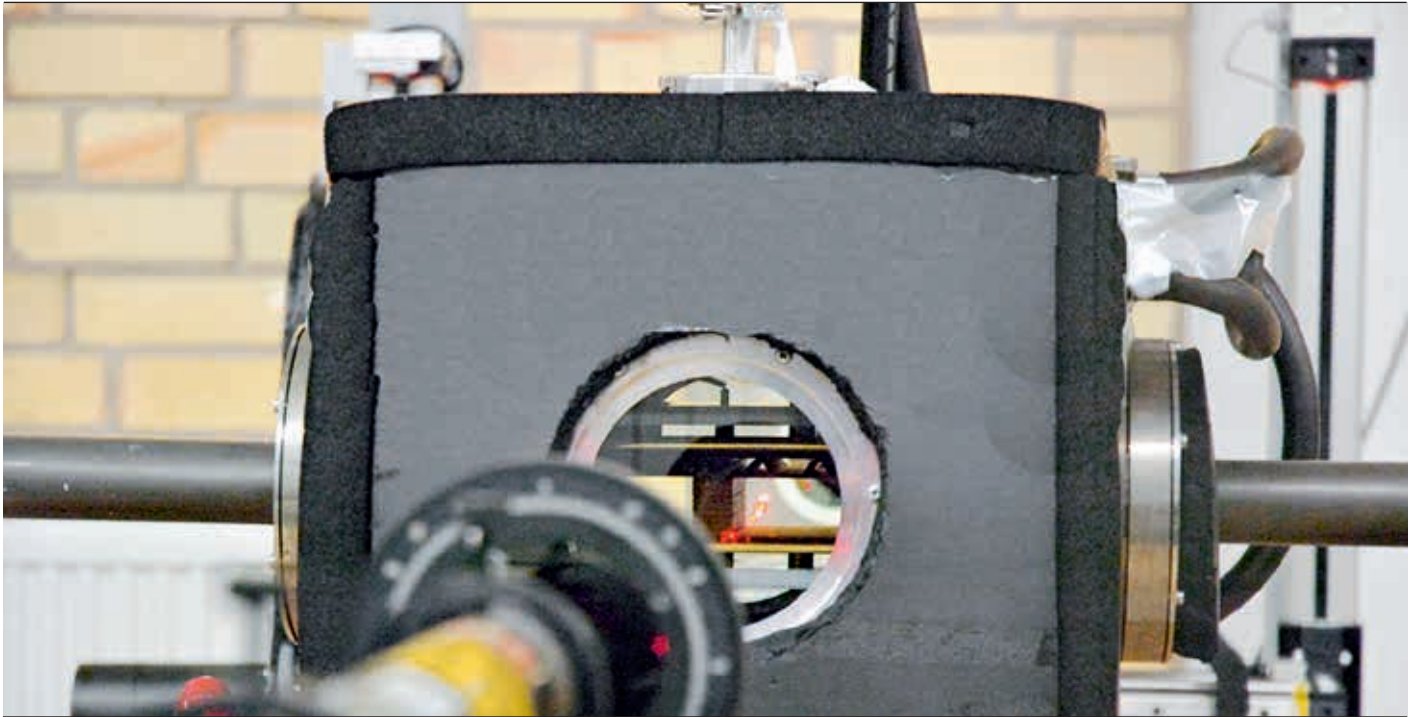
The resistivity of insulation liquids such as mineral oil is not an intrinsic or well-defined material property. The apparent resistivity of such a liquid is defined by the concentration of free ions and their electrical mobility. However, if a liquid is exposed to an electric field, the free ions will start to move along the direction of the field, causing ion depletion – and, thus, reduced resistivity – in certain regions. This means that the apparent resistivity depends on the “electrical stress history” of the oil.

This nonlinear behavior of insulation liquids makes it difficult to use traditional resistive models to predict the electrical field distribution in oil-based insulation systems under DC stress. An alternative to resistive models – the ion drift model – was intro-

The extremely sensitive detection system to measure the electric stress in mineral oil directly exploits the electro-optical Kerr effect.

duced in the 1980s by ASEA researchers [1]. In the ion drift model, transport equations are used to calculate the time-dependent behavior of the ionic density in liquid

5 Experimental setup demonstrating the Kerr measurement technique



The tools, along with associated simulations, enabled the development of the 1,100 kV DC converter transformer prototype in a very short time.

insulation → 4. Using the difference in the density of positive and negative ions, the electrical field can be calculated as a function of time for each position in the system. It is clear from → 4 that solving the equations in three dimensions for many points is computationally demanding. However, modern computers in combination with improved numerical schemes make it feasible to use the ion drift model to design critical parts of the insulation system in converter transformers.

Measurement of electric fields under DC stress in transformer oil

The ion drift model had to be verified by experimental measurement. Therefore, at

the ABB Corporate Research laboratory in Västerås, an extremely sensitive detection system was created to measure the electrical stress in mineral oil directly. The setup exploits the electro-optical Kerr effect, which influences the birefringence of light passing through a liquid dielectric in an electrostatic field → 5. Using this technique, the direction, magnitude and time evolution of the electric fields can be resolved.

The results from the Kerr technique compare well with ion drift model predictions and deviate strongly from the electrical fields predicted from resistive models, as would be expected.

The Kerr technique and the ion drift model – first used for the Itaipu project – have become important tools in the continuous development of insulation systems for converter transformers. These tools, along with associated simulations, enabled the development of the 1,100 kV DC converter transformer prototype in a very short time. The design tools, together with a deep understanding of the phenomena involved, have significantly contributed to ABB's technical leadership when it comes to HVDC and UHVDC converter transformers.

The results from the Kerr technique compare well with ion drift model predictions.

Joachim Schiessling

Olof Hjortstam

ABB Corporate Research

Västerås, Sweden

joachim.schiessling@se.abb.com

olof.hjortstam@se.abb.com

Mats Berglund

ABB Power Grids, Transformers

Ludvika, Sweden

mats.g.berglund@se.abb.com

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Microgrids

How microgrids can cut costs, emissions and enhance reliability

TILO BUEHLER, RITWIK MAJUMDER – Is brain better than brawn? Or do we need both? Looking back, traditional power grids allowed end users little of either. Generating plants and control decisions were located in distant places and users had little control over their provenance or cost. Today, generation is no longer the exclusive domain of large power plants: Rooftop solar and other forms of distributed generation are blurring the distinction between producers and consumers. But it is not just the brawn that is becoming accessible to all. Increasing levels of embedded intelligence and controllable switches are permitting the decentralization of control decisions. Owners of large sites such as hospitals or factories are now able to control their own power networks and so reduce costs and emissions.

Power grids are undergoing a revolution on a scale not seen since power distribution first emerged. The increasing share of local generation is leading to changes in the way grids are managed.

There is nothing new to sites such as hospitals and factories maintaining some form of backup generation for emergencies, typically in the form of diesel generators. In recent years, local generating capability has often been augmented by the installation of photovoltaic cells, sometimes in conjunction with battery storage. In contrast to the emergency generators, which are provided primarily for supply security reasons, owners wish for these additional investments to be used as extensively and as profitably as possible. What emerges is a strategy for optimal deployment of both internal and external power generating capacity.

Microgrids can take many different forms and be of different sizes and geographic distributions. In fact varying formal definitions of microgrids exist → 1.

but all microgrids share these common features:

- have multiple sources and loads
- be distributed
- be controllable and have some autonomy of control

The purpose of a microgrid can be similarly varied. Typically microgrids are installed to:

- reduce costs
- reduce environmental footprint
- assure security of supply

Increasing levels of embedded intelligence are permitting the decentralization of control decisions.

Microgrids can either be grid-connected (as in the hospital and factory examples above) or completely standalone, for example in a geographically remote location → 2. ABB contributed to the microgrid for Kodiak Island off the Alaskan coast. The island with 15,000 inhabitants and no external grid connection covers virtually all its electrical needs from renewable sources. ABB's scope of delivery includes flywheel-based energy storage.

1 Definition of microgrids

Different definitions exist for microgrids.

According to the U.S. Department of Energy Microgrid Exchange Group, a microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.

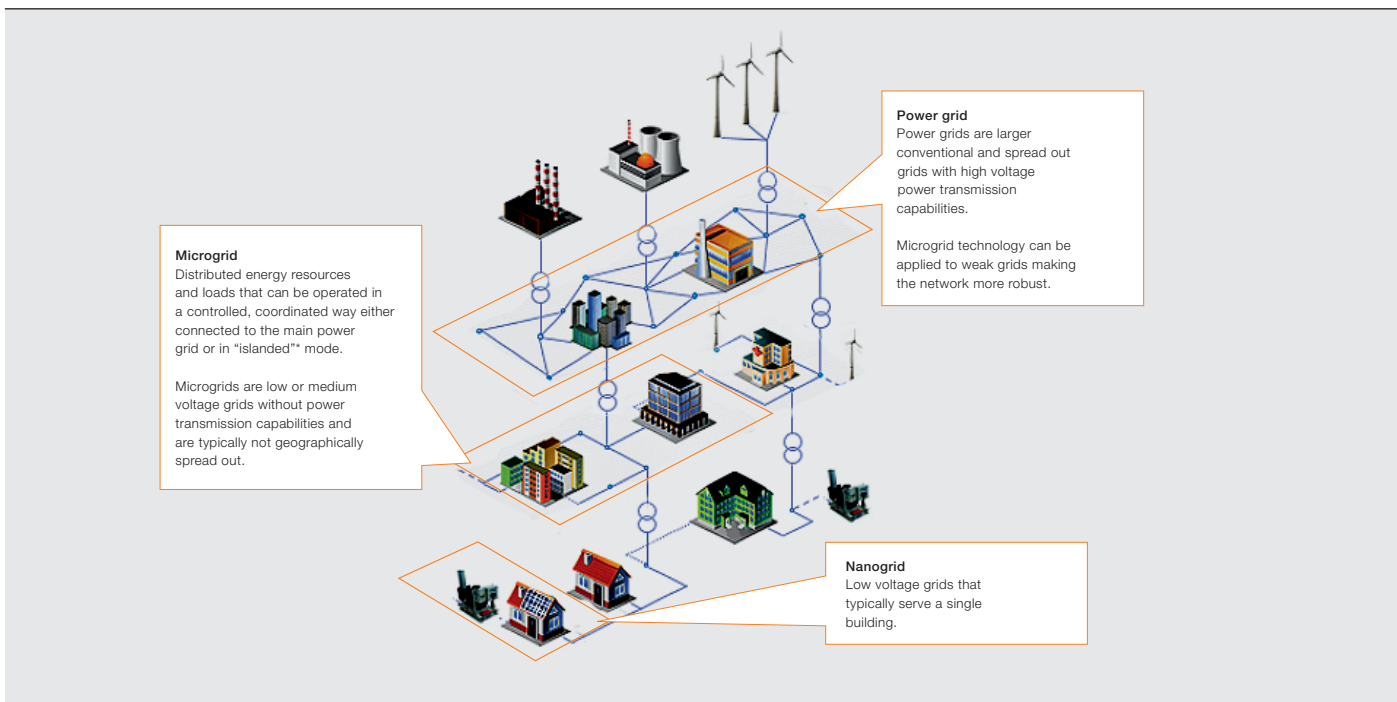
The CIGRÉ C6.22 Working Group, Microgrid Evolution Roadmap says microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.

2 Microgrid segments and main drivers covering a diverse range of applications

		Main drivers					
		Social	Economic	Environmental	Operational		
Segments	Typical customers	Access to electricity	Fuel & cost savings	Reduce CO2 footprint and pollution	Fuel independence	Uninterrupted supply	
<div style="display: flex; flex-direction: column; align-items: center;"> <div style="width: 10px; height: 20px; background-color: #8B4513; margin-bottom: 5px;"></div> Off-grid <div style="width: 10px; height: 20px; background-color: #FF8C00; margin-bottom: 5px;"></div> Weak grid <div style="width: 10px; height: 20px; background-color: #A9A9A9; margin-bottom: 5px;"></div> Grid-connected </div>	Island utilities		✓	✓	✓	(✓)	
	Remote communities	✓	✓		✓		
	Industrial and commercial			(✓)	✓	✓	
	Defense	Governmental defense institution		(✓)	(✓)	✓	✓
	Urban communities	(Local) utility, IPP			(✓)		✓
	Institutions and campuses	Private education institution, IPP, Government education institution		(✓)	✓		(✓)

IPP: Independent Power Producer ✓ Main driver (✓) Secondary driver

3 A microgrid can be considered an intermediate between wide-area power grids and very local nanogrids.



One way of looking at a microgrid is to consider it a smaller version of the power grid. A microgrid faces much the same challenges as its larger cousin. It has diverse energy sources, different consumers and can in many cases exchange power with other grids through interconnections. There are also significant differences, caused for example by low inertia, high penetration of renewables and the effects of controlled power electronics. A microgrid controller must balance

available resources in a manner that is safe, economical and assures security of supply → 3.

In some situations microgrids may be provided to mitigate reliability of the supplying grid. In a hospital there is no question of halting a life-saving operation because the lights are going out, and in an industrial plant an unplanned stop can lead to large financial losses. Ideally (and if the controller has the appropriate

functions), a microgrid can seamlessly transition from grid-connected mode to island mode. It deploys available generation and storage while shedding loads if necessary and also prevents the tripping of local protection devices. The controller must similarly support grid reconnection when this becomes available.

ABB can look back on more than 25 years of experience and more than 30 completed microgrid projects → 4. The company is a

Local generating capability has often been augmented by the installation of photovoltaic cells, sometimes in conjunction with battery storage.

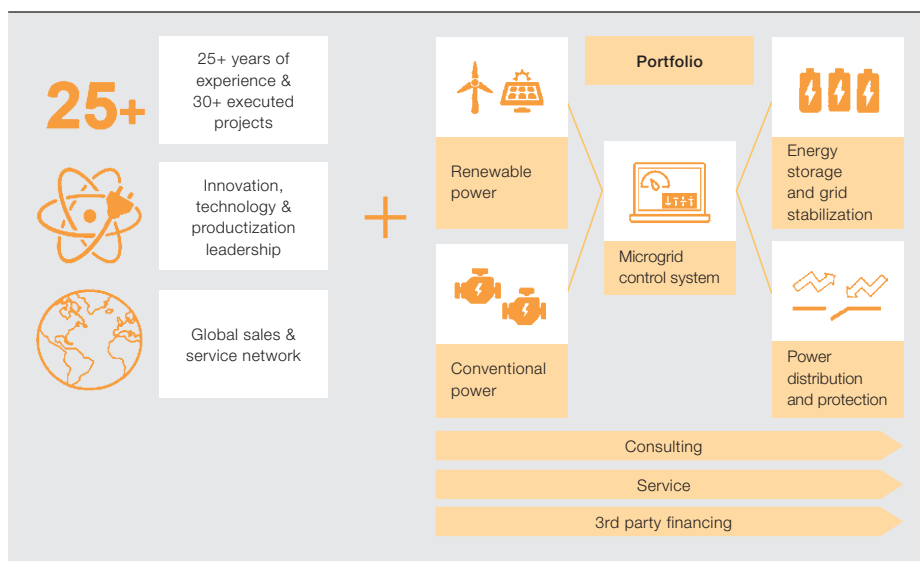
4 ABB is practicing what it preaches

ABB is installing an integrated solar-diesel microgrid at its Longmeadow premises in Johannesburg, South Africa. The 96,000 m² facility houses the company's country headquarters as well as medium voltage switchgear manufacturing and protection panel assembly facilities, and has around 1,000 employees. The scope of delivery includes a rooftop solar photovoltaic (PV) field and a PowerStore™ grid stabilizer that will help to maximize the use of clean solar energy and ensure uninterrupted power

supply to keep the lights on and the factories running even in the event of a power outage on the main grid supply.

A 750 kW rooftop PV plant and a 1 MVA/380 kWh battery-based PowerStore will be added to the existing back-up diesel generators. This will enhance the use of renewable energy and provide continuity of supply when power supply is disrupted and during transitions from grid to island operation.

5 With more than 25 years of experience and more than 30 executed microgrid projects globally, ABB is the leading provider of products and solutions for microgrids.



leading provider of products and solutions across power generation, including renewables, automation, grid stabilization, energy storage and intelligent-control technology as well as consulting services to enable microgrids globally → 5. The company's position in the microgrids segment was strengthened through the 2011 acquisition of Powercorp.

ABB's corporate research centers have been at the forefront of advancing microgrid technology by doing research into such areas as storage, stability, protection and interconnection.

The ABB's Microgrid Plus control solution consists of the company's Microgrid Plus System™ control system and the PowerStore™ flywheel or battery-based grid stabilizing system. The controller calculates the most economical power configuration, ensuring a proper bal-

ance of supply and demand that maximizes renewable energy integration, enabling for up to 100 percent use of renewables and high level of stability and reliability.

Besides its controllers and energy storage offerings, ABB contributes numerous other components for microgrids, including its EMAX2 breakers, solar inverters, and grid connectivity, as well as supportive and consulting services.

Tilo Buehler

ABB Power Grids
Baden-Daettwil, Switzerland
tilo.buehler@ch.abb.com

Ritwik Majumder

ABB Corporate Research
Västerås, Sweden
ritwik.majumder@se.abb.com

Robot bio

The life and times of the electrical industrial robot

TOMAS LAGERBERG, JAN JONSON – A new age of industrial automation was ushered in when the electrical industrial robot was born in Västerås, Sweden in the early 1970s. This is the story of the origins and the current state of industrial robots, and a look into their exciting future and the promise they hold for mankind.

The story of the industrial robot started in 1954 when George Devol patented the first teachable robot. In 1956, Devol and Joseph Engelberger (later dubbed “the father of the industrial robot”) started the first robot company (Unimation). The first Unimation robot, which was hydraulically driven, was sold to General Motors in 1961 and Unimation’s business started to get interesting when, in 1964, General Motors ordered no less than 66 robots. The first robot in Europe was installed in 1967, at Svenska Metallverken in Upplands Väsby, Sweden.

The potential of robots did not escape the attention of ASEA’s CEO, Curt Nicolin, who came to the conclusion that ASEA should develop their own. This was the genesis of the electrical industrial robot. In the summer of 1971, Nicolin had two of his top engineers, Ove Kullborg and Curt Hansson, look into new approaches to robot design, given that the Unimation products were big, noisy, energy-consuming beasts that leaked copious amounts of oil.

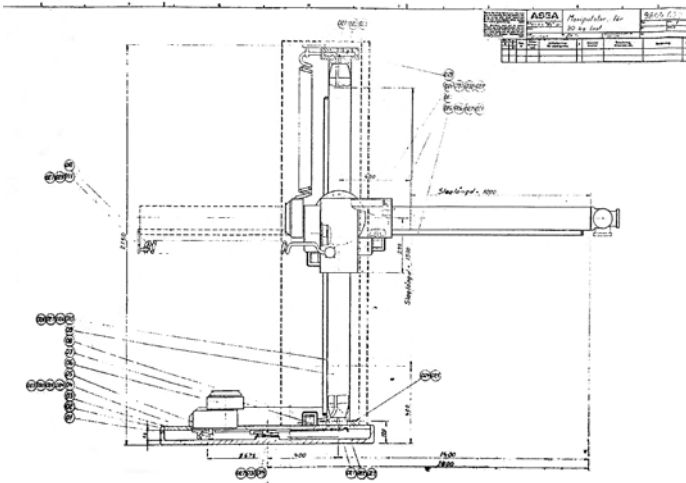
Ove Kullborg and Curt Hansson jotted down some initial ideas. Eventually, a five-axis “manipulator” (the word “robot” first appeared on drawings in 1972) concept was developed; it had an arm that moved vertically and horizontally as well as swung around its base → 1-2.

In April 1972, the ASEA board of directors made a decision to launch a full-scale robot development project and an up-and-coming automation specialist,

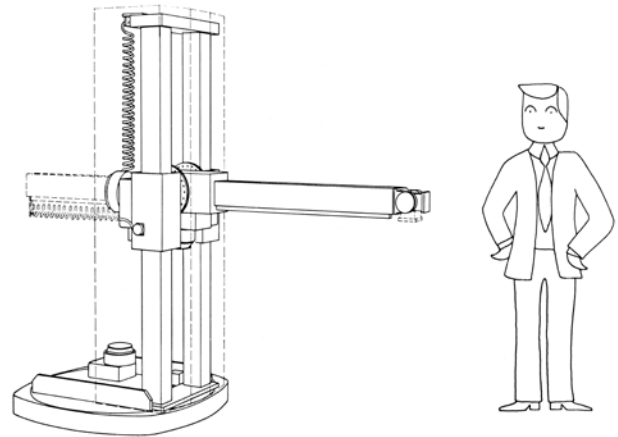
The electrical drive system developed by Ove Kullborg’s team was the clear winner.

Björn Weichbrodt, was chosen as project leader. A first prototype was to be shown to the board in February 1973. The project, from the start, included everything from mechanical design and electronics to marketing and application development. The task of developing the mechanical design was taken up by senior designers Ove Kullborg and Bengt Nilsson, each of whom was given the responsibility for a team of around 10 mechanical engineers.

1 Initial five-axis concept, including a simple drawing to show proportions



1a One of the early ASEA robot concept drawings



1b The original ASEA robot was to be just over 2 m high

Today, ABB has a large family of industrial robots and has shipped and installed well over 250,000 robots.

An early fundamental choice was the drive concept: hydraulic, pneumatic or electrical? Pneumatics were ruled out due to lack of stiffness in the drive chain, making accuracy and repeatability virtually impossible. Hydraulic robots were prevalent at the time and electrically driven ones rare. To decide which approach should be taken, an internal competition was held in which two teams – lead by Kullborg and Weichbrodt, respectively – designed and built prototypes of the lower three axes of both an electrical and a hydraulic drive train. These were then run side by side. The electrical drive system developed by Kullborg's team was the clear winner.

Another important design choice was the basic robot design. During his time in the United States Weichbrodt had seen prototypes of anthropomorphic robots, ie, robots that mimic the movement pattern of the human arm. He saw this as the way forward for the upcoming ASEA robot.

The third key design choice involved the electronics and programmability of the robot. It was clear early on that conventional electronics provided inadequate flexibility, accuracy and stability. However, a team member had read about a new device called the 8008 microprocessor, developed by an obscure American company called Intel. It was small and could be embedded into control electronics to provide full programmability of the controlled device. The manual the

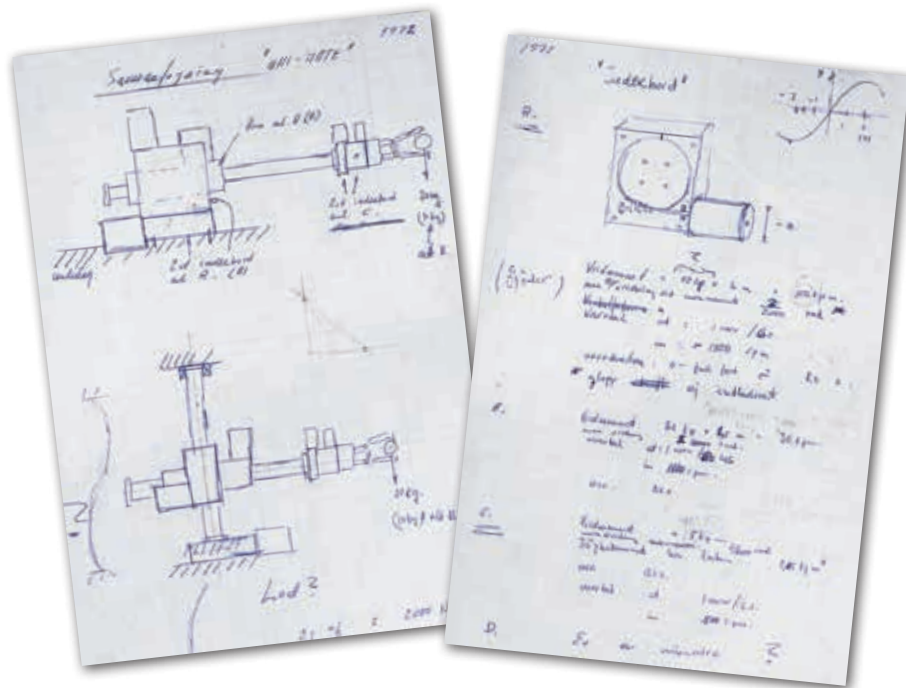
team requested and received from Intel was, appropriately enough, manually typed with handwritten corrections and had been photocopied many times, which made it hard to read. The team understood enough, though, to realize that the 8008 was exactly what they needed.

Prototype boards were wired with the electronics, but no microprocessors were yet available so the design and code could not be tested. In the end, Weichbrodt had to travel to Intel in California to pick up two microprocessors. The resulting design was a state-of-the-art electronic control system including a basic teach pendant and user interface.

Three basic design decisions had now been made: The ASEA robot was to be electrically driven, anthropomorphic and microprocessor-controlled – features that are nowadays taken for granted.

The IRB 6, as it was now named (Industrial RoBot/6 kg payload), attracted much attention on its public debut in October 1973, when it demonstrated how to pick valve blocks and place them in patterns. The IRB 6's potential was spotted by Magnussons i Genarp, a small workshop in the south of Sweden that, on New Year's Eve, 1973, placed the very first IRB 6 order. Later, in 1974, Magnussons ordered four more IRB 6s and today, more than 40 years later, four of them still perform the same task – polish stainless steel tubes. ABB bought back the

2 Early design sketches



first IRB 6 a few years ago to use as a museum piece.

As with all new and revolutionary products it took some time for volumes to pick up, but by 1978, sales had become large enough to generate a positive cash flow for the ASEA robot business.

Jump now to 2014 and the ABB Capital Markets Day in London. Apart from the usual financial figures and strategy presentations, also revealed to the world for the first time was a new member of the ABB robot family – YuMi®. YuMi was launched as the world's first truly collaborative robot and had been designed from the start to collaborate with humans. Hence the name YuMi: you and me.

The motivation for YuMi came about in 2006 when the need was identified for a robot that could be used in, for example, small-part assembly in mobile phone and small electronics plants in China. The

current assembly plants were almost entirely manual, with thousands of assembly workers standing side by side. It was clear that the robot would have to be able to work beside humans and that it would have to fit in the same space as its human colleagues. This vision, as depicted by a professional illustrator → 3, inspired the team throughout the whole project.

The robot's safety features were paramount. These included two arms (for speed reduction), soft padding on the arms, no-squeeze zones in the joints, lim-

Three basic design decisions had been made: The ASEA robot was to be electrically driven, anthropomorphic and microprocessor-controlled – features that are nowadays taken for granted.

ited payload, and limited motor speed and torque. Camilla Kullborg, a mechanical designer in the project, realized that it was

The third key design choice was in the electronics and programmability of the robot.

3 The vision for the YuMi project



4 YuMi – The world's first truly collaborative robot



The IRB 6 attracted a lot of attention on its public debut in October 1973.

not enough for the robot to be safe – it also had to feel and appear safe and from this insight emerged the initial design that finally led to the YuMi that exists today → 4. In 2011, Camilla Kullborg and the YuMi development team were honored with the prestigious “red dot: best of the best” industrial design award.

YuMi was extremely well received and when the product was released for sale at the Hanover Fair in 2015 it was the star of the show. It is no exaggeration to say that YuMi marks the birth of a new era of robotics – the era of truly collaborative robots.

Today, ABB has a large family of industrial robots and has shipped and installed well over 250,000 units, including many world-firsts in robotics: the first arc welding robot, the first electrical paint robot, the first teach pendant with joystick, the first AC drive system on robots, the first virtual robot technology, the first high-level robot programming language, and the first modular robot family. And all that from a humble beginning in 1972 with Björn Weichbrodt – the “father of the electrical robot” – and his first robot.

The industrial robot market is expected to grow rapidly in the coming years. Completely new types of robots are likely to appear: flying robots, swimming robots, walking robots, rolling robots, mi-

cro robots, robots mounted on vehicles, robots that augment human strength and robots that support and collaborate with people – perhaps even in outer space.

Agnes Kullborg, nine year old, daughter of Camilla Kullborg and granddaughter of Ove Kullborg, put her finger on it when asked about the future of robots: “Robots are really cool and they help people. I think that in the future they will help people even more. I’d be interested in working with robots. Maybe design how they are going to look. Maybe something like a future YuMi, because it looks really friendly.” Agnes, representing the third generation in this Kullborg robot family, is, of course, entirely correct.

Tomas Lagerberg

ABB Corporate Research
Västerås, Sweden
tomas.lagerberg@se.abb.com

Jan Jonson

Former ABB employee
ABB Discrete Automation and Motion, Robotics
Västerås, Sweden

A stirring history

Sustained innovation sums up the history of ABB's electromagnetic products

REBEI BEL FDHILA, ULF SAND, JAN ERIK ERIKSSON, HONGLIANG YANG – The evolution of ABB's electromagnetic products in the metals industry has been a long and impressive one, full of patents, pioneering minds, respected personalities, significant industry contributions and market leading innovations. With its foothold in the metals industry established early on, ABB has embraced opportunities along the way to engage customers in a productive collaboration that has solidified its position as a leader and innovator in the industry. This proud heritage serves as a platform for continued excellence in the metals industry and potential entry into new markets.

The electromagnetic stirrer was invented in the early 1930s by Dr. Ludwig Dreyfus, a highly respected employee of ASEA, when he found that sufficient electrodynamic force could be developed in molten metal by means of a traveling magnetic field, and that effective stirring action could be achieved. His patent for electromagnetic stirring in electric arc furnace was granted in Sweden in 1937, which can be considered the birth of electromagnetic stirring and the foundation for all other electromagnetic stirring applications within the metals industry → 1.

First stirrer installation

The first electromagnetic stirrer in practical use was installed in Sweden in 1947 on an electric arc furnace (EAF), which at the time was used as both a melting and refining vessel. The stirrer homogenizes the melt temperature and accelerates the slag-metal reactions. Since then, several thousands of electromagnetic stirrers have been installed in various metal processing applications, such as electric arc furnace, ladle furnace, continuous casting of steel and aluminum re-melting.

World's first ladle furnace

In the 1960s, SKF and ASEA engineers developed the first ladle furnace in the world, the ASEA-SKF, to solve the prob-

lem of poor quality bearing steel production with electric arc furnace. The ASEA-SKF process, with its combination of electromagnetic stirring, vacuum treatment, electric arc heating and argon gas flushing capabilities, was the beginning of a new era of high quality steel production. The first ASEA-SKF ladle furnace went into full-scale production in 1968 in SKF Hällefors, Sweden, and about 70 ASEA-SKF furnaces were

further installed between the 1960s and 1980s worldwide. Although ASEA-SKF was later replaced by more modern ladle refining processes, electromagnetic stirring in ladle (LF-EMS) remained an important tool for efficient production of both commercial and high alloyed steel [1] → 2. Today there are around 140 electromagnetic stirrers installed in various ladle refining processes.

ElectroMagnetic BRake

Implementation of electromagnetic stirring in billet/bloom casters began in the 1970s to improve solid structures and surface quality. In the 1980s, ASEA and Kawasaki Steel applied an electromagnetic field to the conventional slab casting process to further improve slab qual-

ity. This DC magnetic field, acting on the high momentum jet flow from the submerged entry nozzle, reduced the jet speed and stabilized the fluid fluctuation in the mold → 3. The technology, later developed to be an ElectroMagnetic BRake (EMBR), found wider application in the

Today, more than half of all 70 thin slab casters in the world are equipped with an ABB EMBR.

thin slab casting process. The EMBR stabilizes meniscus fluctuations and reduces mold powder entrapments, essential for high speed casting operation and assuring thin slab quality. Today, more than half of all 70 thin slab casters in the world are equipped with an ABB EMBR.

Flow Control Mold

In the 1990s Kawasaki Steel (later JFE) and ABB developed a Flow Control Mold for conventional slab casters. The FC Mold, keeping the DC magnetic field in the lower part of the mold, adds one level DC field in the upper area of the mold to stabilize meniscus fluctuation, thus increasing flexibility in controlling flow conditions. Kawasaki Steel achieved superior results with the FC mold including

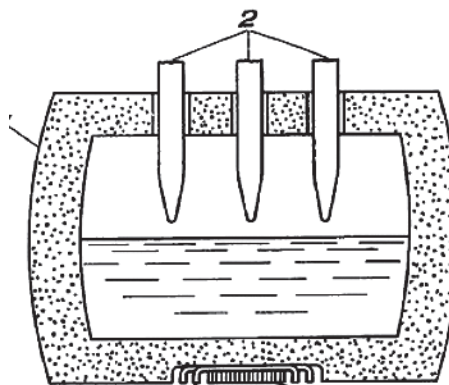
PATENT N^o 102334 SVERIGE **KLASS 21: h: 18-10**
 BESKRIVNING
 OFFENTLIGGJORD AV KUNGL.
 PATENT- OCH REGISTRERINGSVERKET
 BEVILJAT DEN 19 JUNI 1941
 GILTIGT FRÅN DEN 22 JAN. 1937
 PUBLICERAT DEN 19 AUGUSTI 1941
 Ans. nr 281/1937. *Härtill en ritning.*



ALLMÄNNA SVENSKA ELEKTRISKA AKTIEBOLAGET, VÄSTERÅS.
Omröringsanordning vid ugnar för metallurgiska ändamål.
 (Uppfinnare: L. Dreyfus.)

Det är bekant att vid s. k. virvelströmsugnar, d. v. s. ugnar vid vilka den huvudsakliga värmetillförseln till chargen sker genom i densamma inducerade elektriska virvelströmmar, vanligen av hög frekvens, åstadkomma en elektrodynamisk omröring av chargen eller lödet i syfte att påskynda där förlöpande reaktioner. I de ändamålsenliga formerna av de

i huvudsak kring en horisontal axel, så att nya delar av detsamma oppbörigt komma upp till ytan samt där utsätts för uppvärmning resp. reaktioner. Samtidigt hålles periodtalet av strömmen i omröringsanordningen väsentligt lägre än lästa kommersiella periodtal, varigenom effekten i nämnda bindning hålles låg. Någon nämnvärd uppvärmning avses såväl hindras



The FC Mold G3 is the most advanced flow control equipment available on the market for slab casters.

increased casting speed and improved slab internal and surface quality. Today, more than 70 strands are benefitting from the outstanding technology of the FC Mold for conventional slab casters.

Flow Control Mold G3

In the 2000s ABB developed the third generation FC Mold (FC Mold G3) to meet the new market demands for conventional slab casters. The FC Mold G3 adds a traveling magnetic field in the same position of the upper DC magnetic field as the FC Mold II that can function simultaneously with the AC magnetic field, which controls meniscus speed into the optimum range at almost all casting conditions → 4. The FC Mold G3 is the most advanced flow control equipment available on the market for slab casters. Now in 2016 ABB will launch OptiMold Monitor, a product offering mold temperature measurement in continuous casting. Providing unparalleled process insight, this technology can be combined with the FC Mold to allow for real-time process control, taking end product quality to the next level.

Aluminum re-melting furnaces

In the 1960s, ASEA developed an electromagnetic stirrer for aluminum re-melting furnaces (AL-EMS), which showed convincing results in energy savings, yield and productivity increases. However, it only received adequate attention in the 1990s when the aluminum industry realized the necessity for energy savings and productivity increases. ABB then introduced a series of AL-EMS for the entire

spectrum of furnace sizes and types → 5. For typical aluminum re-melting furnaces, the AL-EMS can deliver energy saving of 10 percent and increase productivity by 25 percent. Today ABB has installed more than 200 AL-EMS around the world.

ArcSave®

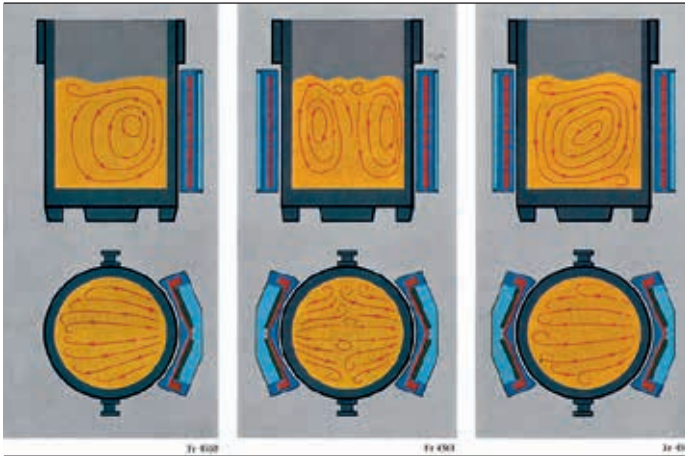
Since the 1980s, the electric arc furnace has gradually become purely a melting vessel with high power consumption and short melting time. In the early 2000s, ABB developed a new stirrer with a much stronger stirring capacity. This stirrer was later patented and commercialized as ArcSave® and was installed on a modern EAF, showing clear customer benefits in energy saving, iron yield, alloys savings and more.

Industry pioneers and continuing innovation

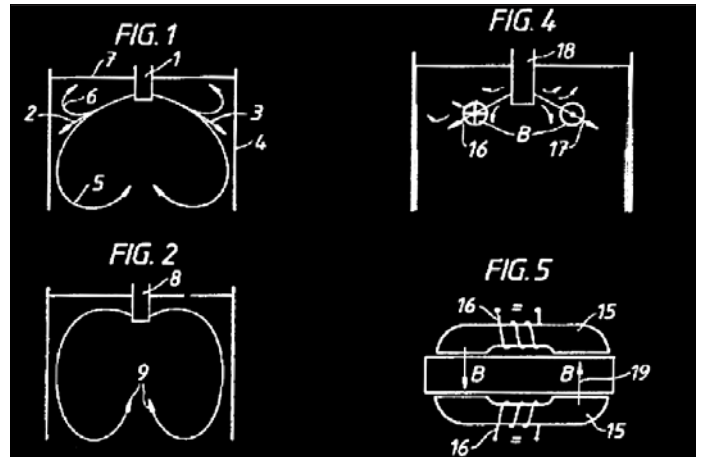
In addition to the invention of the electromagnetic arc stirrer by Dr. Dreyfus, several ABB employees have been true innovators in the industry. Just a few highlights include:

- Yngve Sundberg, employed in the 1950s–1980s, developed a complete theory covering calculation and design of electric furnaces and electromagnetic stirrers. He and his former ASEA colleagues hold at least six patents and his “Electric Furnaces and Inductive Stirrers” is referred to frequently in the industry even today [2].
- Sten Kollberg’s exceptional focus on issues in the customer’s casting

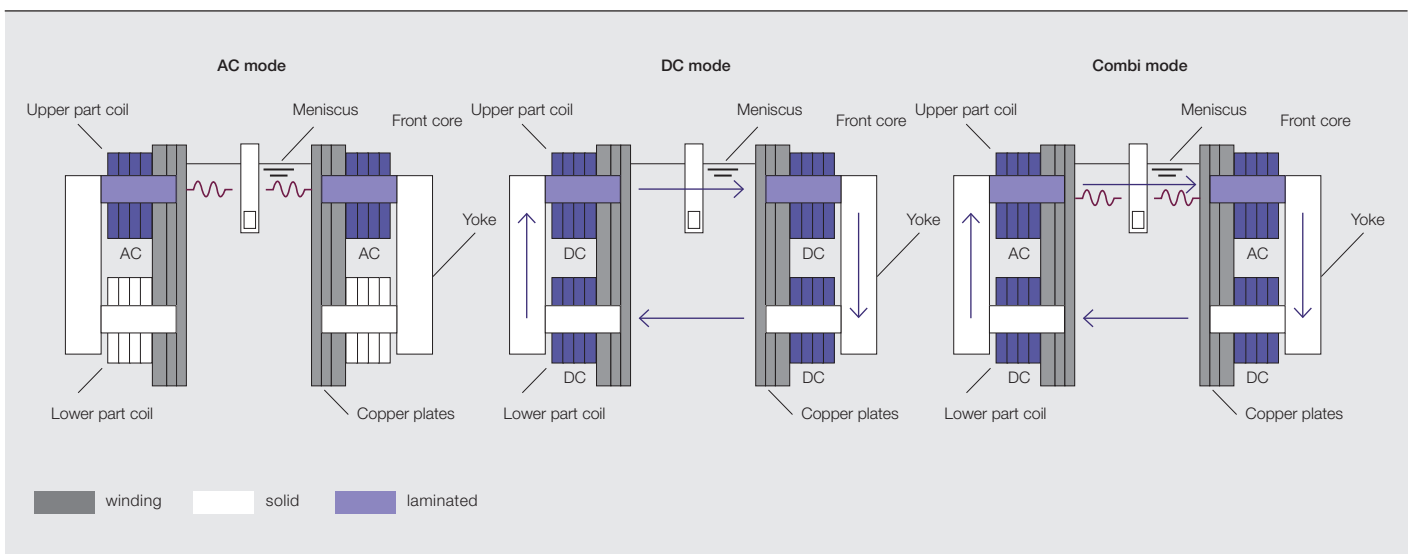
2 Different stirring pattern sketched in the early stage of ASEA-SKF process



3 First patent on EMBR in slab caster.



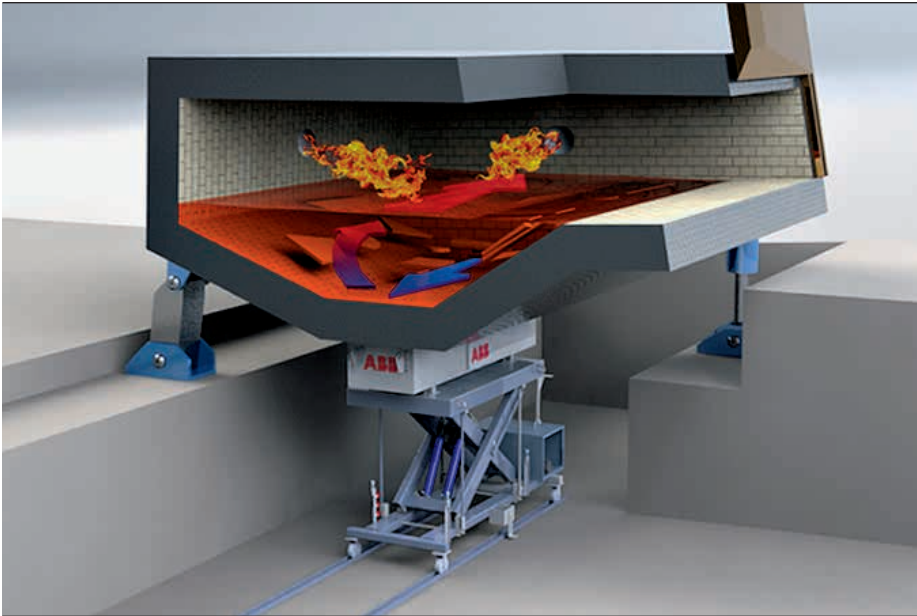
4 Operation modes of FC Mold G3



A deeper collaboration with ABB Corporate Research in the last two decades . . . has led to advanced measurements and simulation techniques . . .

process in the 1980s–1990s paved the way for the development of the EMBR and the FC Mold. He was highly respected for his people skills and ingenuity.

- Göte Tallbäck, who worked at ASEA at around the same period as Sten, introduced magnetohydrodynamics (MHD) into metallurgical processes. His paper, published 30 years ago on the numerical simulation of the EMBR process, is still being cited today. In the 2000s, he and his ASEA colleagues registered four patents for electromagnetic stirring.
- Jan-Erik Eriksson, with ABB since 1980, boasts 25 patents, together with his ABB colleagues. Jan-Erik has been instrumental in the ongoing development of the FC Mold, particularly the latest generation, and the EMBR in conjunction with Japanese industry partners.
- Rebei Bel Fdhila, who joined ABB Corporate Research in 1995, is applying his deep modeling competence together with his colleagues'



process experience to help ABB reshape its modeling, simulation and design capabilities to offer important new features in electromagnetic stirring technology and to solidify its market position.

A deeper collaboration with ABB Corporate Research in the last two decades, influenced by Rebei Bel Fdhila and Jan-Erik Eriksson, has led to advanced measurements and simulation techniques, including several types of laser based measurements and state-of-the-art Computational Fluid Dynamics. The deep fundamental knowledge of metallurgy, the continuous casting, the electromagnetic field effect and the underlying complex phenomena associated with the multi-phase flows in which the liquid metal, the argon gas, and particles strongly interact, allowed the R&D ABB team to successfully improve and modernize the EMS technology with new features to enter into new markets.

Development demands and driving force

Energy efficiency, productivity and quality are fundamental to the sustainable development of the metals industry and electromagnetic stirring and braking have an important role to play moving forward. Products such as ArcSave®, the new generation of the FC Mold and the OptiMold Monitor are but a few examples of ABB's contribution and they

demonstrate ABB's ability to understand and meet market demand with technological innovation. As the internet of things, services and people (IoTSP) raises expectations within the metals industry in the coming years, ABB will focus on developing products that deliver not only improved safety and reliability, cost-efficiency and quality, but that are easier to use, can measure and analyze, and that improve process performance for our customers. ABB has had the privilege of working with nearly all the leading steel manufactures around the world and is committed to remaining at the forefront of electromagnetic product innovation in the metals industry.

Rebei Bel Fdhila

Ulf Sand

ABB Corporate Research
Västerås, Sweden
rebei.bel_fdhila@se.abb.com
ulf.sand@se.abb.com

Jan Erik Eriksson

Hongliang Yang

ABB Process Automation, Metallurgy
Västerås, Sweden
hongliang.yang@se.abb.com
jan-erik.a.eriksson@se.abb.com

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- [1] Sundberg, Y. (1971). *Principles of the induction stirrer*. ASEA Journal, 44 (4), 71–80.
- [2] Sundberg, Y. (1979). *Electric furnaces and induction stirrers*. Västerås: ASEA.

Sense of ore

Mining 2.0 – Automation solutions for the mining industry

JAN NYQVIST – Out of sight may be out of mind for some, but not for those with an interest in mining, and that includes ABB. Mining 2.0 is about developing automation solutions for the mining industry. The target sector is underground mining and the concept includes some unique solutions for the market. Mining 2.0 addresses an industry in transformation with solutions for the whole value chain and with the vision of creating an “ore factory” → 1. The basic idea was to introduce process control methods into discrete mining operations. An approach that in the beginning was new for the market but today the mining community is actively seeking and driving such automation solutions.

Mining, as producers of raw material for our wellbeing, is an important industry for the development of the world. The sector is global and is often a strategic commercial area for regions. There are around 10,000 underground mines and ABB’s primary focus is on the metals market which includes commodities such as iron, copper, nickel, gold, silver, zinc and lead.

Mining, the community

The mining industry is currently facing dramatic price drops of commodities and many new or recently started mining projects have been postponed or closed. Typically the price drops have been between 30 to 50 percent and even more for iron. The industry is being driven by high growth in emerging countries and at the same time new exploration is being done in more remote locations and moving underground or deeper underground with up to 50 percent lower mineral content for some commodities. As a result, producing the same value requires much more ore to be extracted from increasingly difficult locations.

The mining industries priorities are:

- Safety
- Efficient production
- Environmental impact
- Workforce recruitment and retention

Typical mining operation characteristics are:

- Harsh environment and high risk areas
- Long distance and limited space
- High degree of unplanned activities
- High degree of human and mobile machines involved
- Utilization of mobile machines can be as low as 20 to 25 percent
- Utilization of open faces, can be as low as 20 to 30 percent
- Limited visibility of ongoing operation in real time

Mining and ABB

ABB has a portfolio of solutions for long term sustainable business on the global mining market. The portfolio is for growth, both with technology and the market needs. Mining 2.0 was the starting point for developing the ABB business for mine automation.

The concept includes some unique solutions for the market, as stated by AngloAmerican: *“We have not seen any similar. You have something unique in your concept”* or by RioTinto *“if we had have this solution, we would increase our production with 10 to 20 percent.”*

Technologies developed in Mining 2.0 have resulted in the development of several product concepts such as MineInsight, Smart ventilation and Integrated Mining Operations (IMO). Parts of the concepts have been introduced to the market and others are under development.

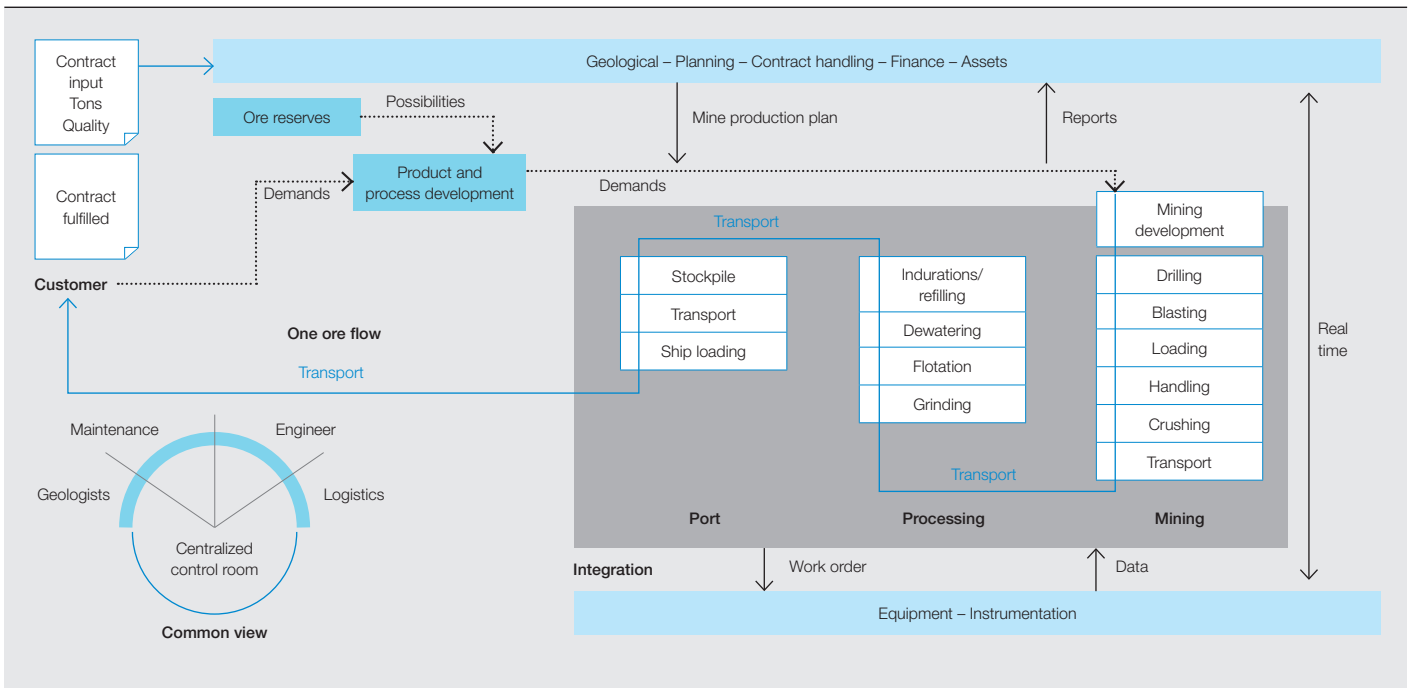
Mining 2.0 is a result of open and sharing collaboration between ABB’s Mining business unit and Corporate Research (CR) within ABB but also interaction with

Producing the same value requires much more ore to be extracted from increasingly difficult locations.

customers, other suppliers, academia and government funded projects, as well as the European Commission’s projects: I²Mine, Rock Tech Centre’s Sustainable Mine and Innovation for the Future (SMIFU) program.

Challenges to meet

One challenge for the project in the early years was to clearly understand and communicate the problems and eventual solutions. The mining industry understood that they had problems and new



“We cannot continue to build larger and larger machines, we need to think in a new way of doing things”.

challenges but struggled to express their findings, on the other hand ABB as a supplier found it difficult to present solutions in an understandable way.

The focus until today has been on increasing the productivity and capacity of the machines to build larger and more mechanically efficient machines, but that solution is close to its limits. As Garvin Yates BHP Billiton says: “We cannot continue to build larger and larger machines, we need to think in a new way of doing mining”. Over time the areas of interest were defined as → 1-2:

- *New mining operation methods* – to move to more continuous mining.
- *Autonomous machines* – using more time for production. A lot of time is consumed by nonproduction activities such as, shift changes, breaks and ventilating the mine after blasting.
- *Machine maintenance* – more preventive maintenance of machines has the potential to improve the utilization of them and reduce unplanned stops in the mine.
- *Remote and centralized control* – A centralized control with an operator supervising all scheduled activities for efficient coordination and acting on disturbances in real time. Doing this remotely means less people need to be on site and several mines can be managed from the same control

center. A large mine can have some hundreds of machines in operation and some thousands of events happen every shift.

- *Efficient ore transport* – Stable transport process avoiding disturbances as running silos ore passes empty, efficient filling of trucks, trains and mine hoist. Running machines efficiently, and only running them to their limit when really necessary → 3.

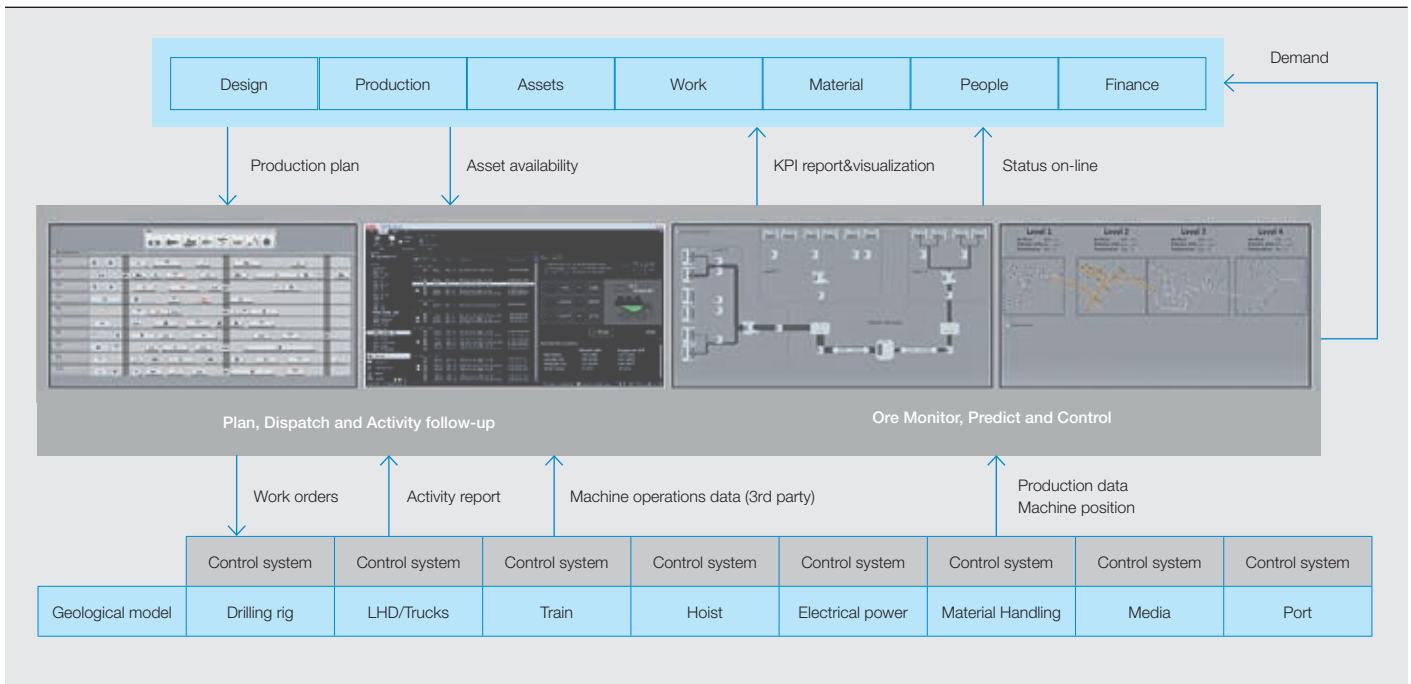
Technology and methods

The developments in Mining 2.0 have included several research areas in CR, such as: communication, user experience, software, sensors and control. The development has been vision based and user driven. Several demonstrations have been developed for displaying and testing scenarios and ideas. Where possible solutions have been evaluated by on site tests.

The technologies used and developed in Mining 2.0 have been:

- *Field studies* – A field study is a team of 2 to 4 people visiting a mine site to observe and conducting interviews to gather information and work flow. This creates the base for further developments:
- *Domain models and architects* – as reference. Describing current and future mining operations.

2 Ore factory as one operation



- *Persona and scenarios* – description of people involved and a workflow for developing user centric automation solutions.
- *Visualization* – different concepts have been developed for different solutions and scenarios → 4.
- *Wireless communication* – has been tested to understand the limitations and how to install in an underground mine. It has also been used to test existing localization → 5 based on wireless communication technologies.
- *Control methods* – has been a key component in mine ventilation, water control, scheduling optimization and material control and tracking.
- *Optimization and statistical methods* – for criticality based optimization of maintenance strategy.

Solutions and products

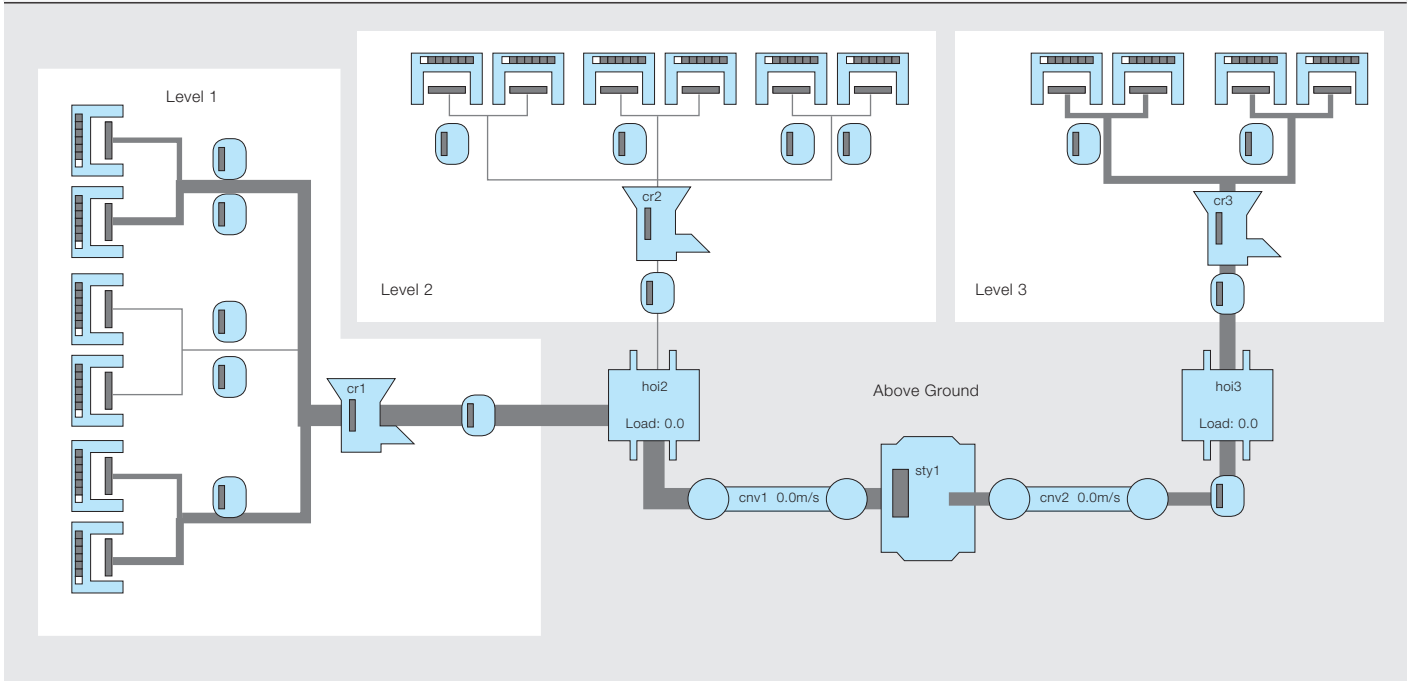
The vision of an “ore factory” was about introducing process control into a discrete process, just as mining is. Key components have been vertical and horizontal integration, centralized control,

single source data and real time access to machine data. The missing piece was the integration of mobile machines enabled through an installed wireless communication network. Solutions developed have been:

- *Maintenance strategy optimization* – CRITICALITY-analysis-based Maintenance (CRIM) optimization tool solves the customer's problem of finding an optimum mixture of predictive, preventive and run-to-failure maintenance

In an underground mine,
technology is a key enabler.
Mine-wide wireless communication allows real time connection to the mobile machines.

strategies for their plants. The developed CRIM optimization process and tools offer one solution to the problem in several steps. Starting with criticality assessment and ending up with life cycle cost analysis (LCCA), the tools help mining customers to analyze and choose the most cost efficient maintenance strategy for the entire plant.



Key components have been vertical and horizontal integration, centralized control, single source data and real time access to machine data.

- *Localization* – of personnel (via their mobile phones) and machines. Via a tagging system machines and personnel can be tracked and visualized in a 3D map of the mine. Geofences for safety zones can be built into the system. Productization is done in cooperation with Mobilaris. A product is available on the market named, ABB Mine Location Intelligence.
- The greatest value to the customer is safety but to also make the underground mine more transparent. Everyone knows where everything is.
- *Scheduling optimizer and dispatch* – short term scheduling of all underground activities and online distribution of created work orders to operators. Feedback on progress can be reported back online. Due to the closed loop and optimizer, short term scheduling can be automated. It is a product named MineInsight. The dispatch system is on the market and scheduling should be ready by the end of 2016.
- Customer value is that when unplanned events happen, the time required for unavoidable re-planning is reduced from hours to seconds. As a result a tighter schedule can be done leading to an increase of the production (tests have shown 10 to 20 percent) and thereby improved resource utilization. It will always have

the current status in real time and it will be possible to predict future production.

- *Ore flow control* – is still under development because it has had a lower priority for the market. Material tracking framework is developed and together with visualization concepts it will be part of MineInsight. Customer value is online visualization of ore production, prediction of future production and events, mass balancing through the value chain and an efficient production with minimized disturbances.

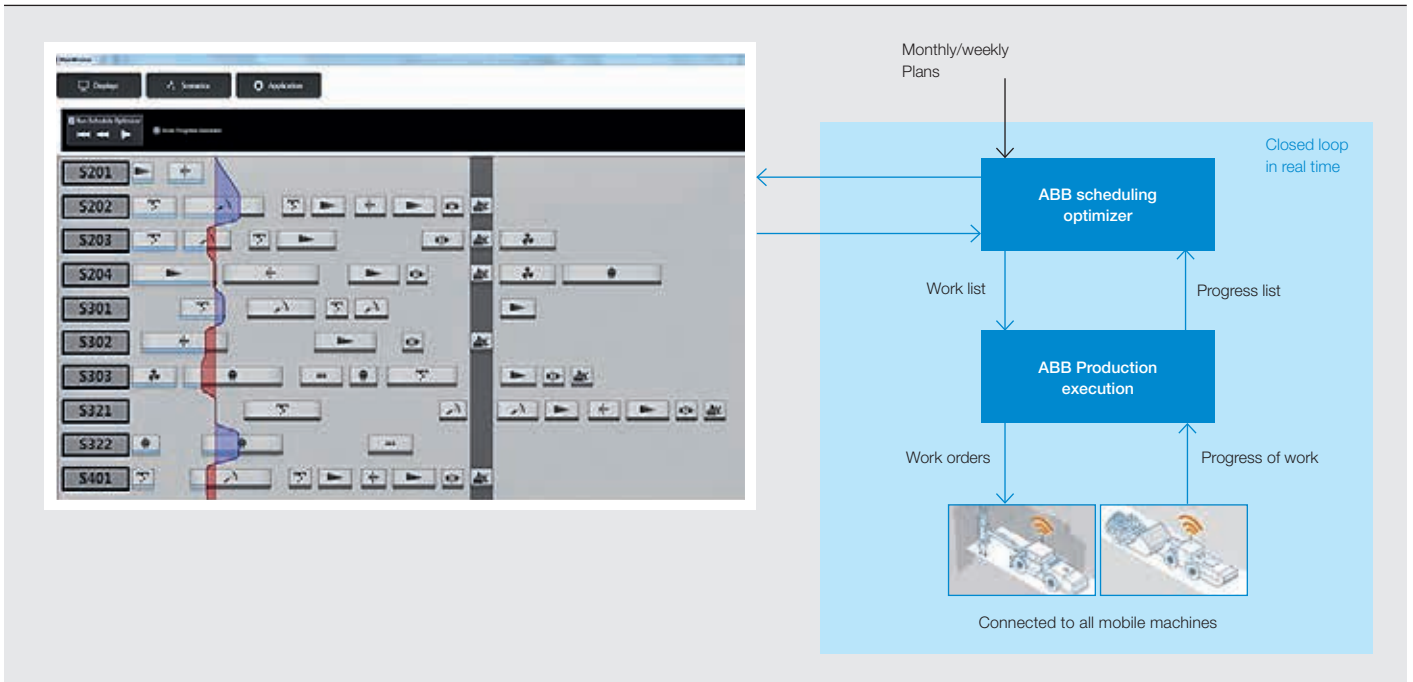
The fifth solution developed has been:

- Mine Ventilation control → 6 – is part of the product ABB Smart ventilation and is ready for the market. All fans and regulators can be controlled via feedback control from sensors.
- Customer value is a robust ventilation system which can easily adapt to new conditions. Fan energy consumption has the potential to decrease up to 50 percent. More efficient use of existing mine ventilation infrastructure (ie, shafts) postponing investments if desired and mine expansion.

The journey of Mining 2.0 – some facts

Mining 2.0 started as pre-study in September 2009. At that time Rio Tinto had stated their concept “Mine of the Future”

4 Automated scheduling with real-time visualization of current status and machine connection



5 Localization of machines and personnel visualized in 3D



Vattenfall AG stated: “our focus is on process optimization where all share information from the same single source”.

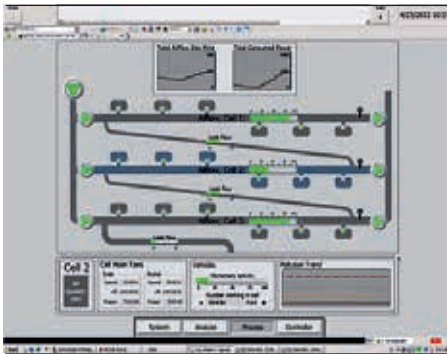
with an ore project called “A pit”. There they would remote control a full mine from a remote operation center (Perth) located 1500 km from the mine (Pilbara region in north west of Australia). Mining 2.0 was the ABB response to the initiative from Rio Tinto with the task: “Mine of the future – what does it mean for ABB?”

During spring 2010 there were two events that were significant for continuation. ABB had started to explore collaboration possibilities with Atlas Copco. The optimized mine was presented in April 2010. Central was the integration of

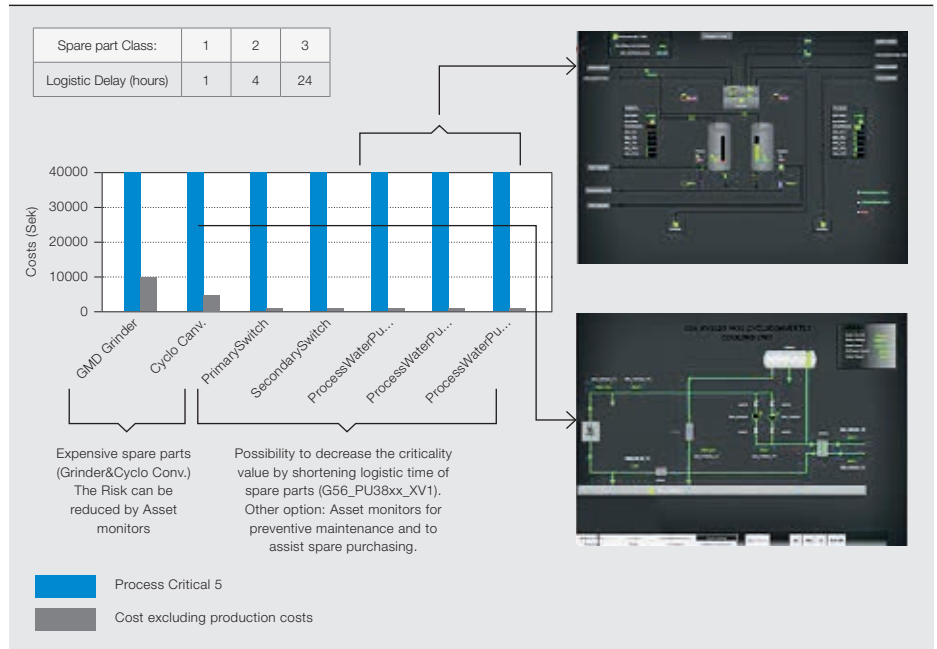
mobile machines and material tracking describing process flow. The second event was a meeting with Vattenfall AG in Germany. Vattenfall AG stated: “We have automated our machines as much as we can, our focus is on process optimization where all share information from the same single source”. Vattenfall also preferred demand control rather than push control which is the normal condition for mine operations and continuous mining.

Summer 2011 – ABB put the vision of an ore factory in place for customer presentations.

6 Mine ventilation control



7 CRIM



The first LTE installed in an underground mine in the world is in Boliden, Sweden. It will be used for the testing of future 5G communications and solutions.

End of 2011 – ABB presented the first solution concepts for an ore factory. The first outputs were the CRIM optimization tool → 7 and method for a cost efficient maintenance strategy had been successfully tested on site and was also presented at the end of the year.

2012 – The concept demonstration is ready, presenting production control through scheduling, material tracking visualization and ventilation. The mine ventilation control was also proved on site with successful results. In 2012 ABB's Mining business unit started to develop the dispatch order system; an essential part of automated scheduling.

2013 – Dispatch systems were developed and a first prototype was installed. CR started to test scheduling algorithms on real data. The algorithms were tested on site by the end of the year.

2014 – MineInsight and Smart ventilation are introduced to the market. The first products, as part of the two concepts, to be sold have been the dispatch system and mine ventilation on demand.

2015 – ABB scheduler is introduced to specific customers and is planned for product release by the end of 2016.

Continuing Mining 2.0

Mining 2.0 has paid attention to the mining market and several relationships have been established with the market. This has been used by other initiatives using mining as their primary target market. Unman the site is one example, developing an industrial mobile manipulation platform and remote control platform. It has resulted in a robot system for the charging process. The results are currently being developed into a deliverable solution.

Remote service including new services such as analytics and service robots, are currently being given attention as a new start-up. Specifically, mine ventilation and power analytics are under development together with conveyor inspection.

The first Long-Term Evolution (LTE) network is currently installed in an underground mine in Boliden, Sweden. The project is called PIMM funded by Vinnova and run in a consortium. It will be the first LTE installed in an underground mine in the world. It will be used for the testing of future 5G communications and solutions.

Jan Nyqvist

ABB Corporate Research
Västerås, Sweden
jan.nyqvist@se.abb.com

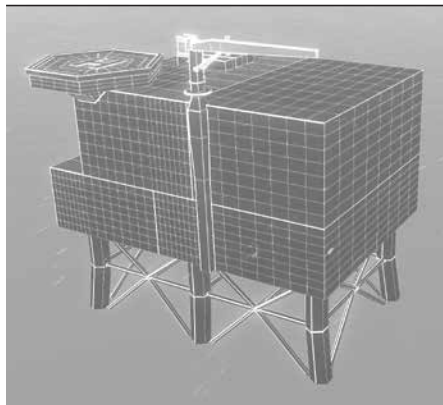


A new compact HVDC solution for offshore wind

HVDC offshore wind compact solution
with half the weight and AC platforms eliminated

RYAN LADD, PETER SANDEBERG – Every offshore wind installation must endure one of the most demanding environments on the planet: the open sea. In a constant battle with wind, waves and salt water they must stand firm and reliably transmit power back to the mainland, often many kilometers distant. Perhaps most challenging of all is the delivery and commissioning of these behemoths: Weighing sometimes over 20,000 tons they have to be transported and positioned by the world's largest vessels and lifted by the world's most powerful cranes. These are operations that can only be carried out in clement weather. ABB's new offshore wind compact HVDC solution changes all this.

1 ABB's new offshore wind compact solution significantly reduces the weight of the platform.



incurred by traditional alternating current (AC) systems. HVDC equipment has many other technical advantages, eg, superior controllability, fast response, blackstart capability, etc. These advantages make HVDC the technology of choice for transmitting power to shore in projects around the world.

A new modular HVDC concept for offshore

Although HVDC is an established technology and has been around for over 60 years, its application offshore is relatively recent. The first offshore HVDC wind project was energized in 2009 and every installation since then has differed significantly from its predecessors, a phenomenon common in a rapidly evolving technology.

The experience and insight gained from implementing HVDC in offshore situations have enabled ABB to come up with a new offshore wind compact solution – one that reduces the weight and volume of the platform by over 50 percent compared to previous designs → 1. Also, the new ABB offshore HVDC solution allows the AC substation platforms currently necessary in the wind farm to be eliminated since the wind turbine generators can now be connected directly to the HVDC platform via a 66 kV collection grid. Eliminating the AC substation platform potentially increases the total weight saving further, up to a total of 70 percent compared to a conventional setup and reduces operational costs by removing the long-term maintenance of these stations. The new HVDC concept is based upon a modular product structure that provides the flexibility to accommodate different

customer specifications. The optimized base-level platform contains everything needed for a fully operational HVDC platform but if for example, there is need for living quarters, a helipad, a more powerful crane or other options, the concept allows them to be easily added – without designing and fabricating an entirely new platform from scratch.

Modular design, of course, has other advantages. Each module can be produced individually, in parallel with others and in more diverse and smaller workshops, as opposed to the traditional fabrication of the entire topside platform in a dedicated yard. This greatly increases the number of suitable suppliers, which provides a more competitive environment and significantly reduces the risks inherent in all such megaprojects.

As well as advantages in fabrication, there are also substantial transportation benefits. There are very few vessels capable of transporting and installing the largest platforms but, with half the weight and the flexibility to distribute the modules between cargo carriers, the new concept represents a step change in logistical management.

A solution for the future

The huge savings in weight delivered by the new HVDC concept have been achieved by close collaboration between ABB's top HVDC engineers and researchers. Innovative thinking has allowed a substantial reduction in the HVDC hardware installed on the platform and extensive studies and tests helped point the way to reduce redundancy while maintaining the required high levels of availability in the system. With improvements to layout and the elimination of excess space, this revolutionary new concept truly represents the next generation of offshore wind solutions.

Ryan Ladd

ABB Power Grids, Grid Systems
HVDC Market Communications
Ludvika, Sweden
ryan.ladd@se.abb.com

Peter Sandeberg

ABB Power Grids, Grid Systems
HVDC Marketing and Strategy
Västerås, Sweden
peter.sandeberg@se.abb.com

With demand for clean, reliable power increasing, wind turbines are becoming a common sight in many countries. However, on land, wind strength can change at a moment's notice and air flows can be disturbed by the presence of hills, trees and cities. At sea, on the other hand, the wind is much more constant and can usually be relied upon to provide a predictable source of power. Also, the number of locations on land suitable for wind turbines is limited – for both practical and aesthetic reasons – whereas wind turbines out to sea are less visible and wind yield is significantly greater offshore. For these reasons, offshore wind turbine numbers are rising rapidly.

Offshore power generation and transmission present challenges, of course. The environment is harsh, facilities have to be accessed for maintenance and there are critical technical obstacles involved in transmitting power great distances under the sea. The problem of transmitting power long distances back to shore efficiently has largely been solved by high-voltage direct current (HVDC) technology, which is not prone to the huge losses

Title picture

New designs of offshore platforms reduce weight by half, simplify the electrical concept and allow a modular approach to construction. These new offshore wind compact solutions look quite different from the familiar platform as shown here.

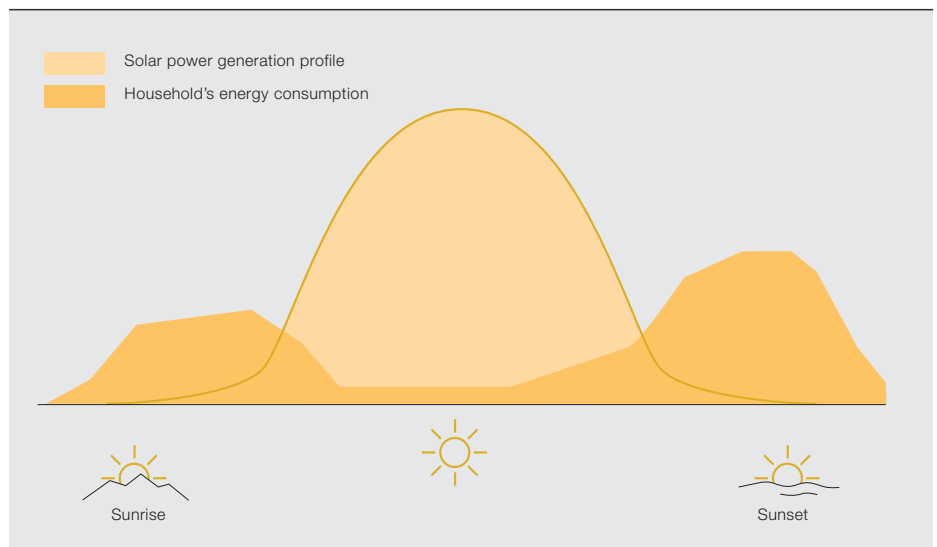


Local savings

Energy storage leads the way for accessible solar in the home

PAOLO CASINI – “The sun is the source of all energy. The world must turn to solar, the power of our future.” Indian Prime Minister Narendra Modi’s statement at the UN Climate Change Conference in Paris in 2015 emphasizes a key goal of the International Solar Alliance launched by France and India: to make solar energy more accessible to all. In fact, solar photovoltaics (PV) have already experienced a tremendous boost since 2004, thanks to schemes like feed-in tariffs (FITs). A fundamental factor that further supports this growth and contributes to the financial and technical sustainability of solar PV is energy storage. The addition of energy storage to solar will drive the next generation of PV systems. Solar as we have known it will likely look decidedly different in the future – especially in the residential arena – and ABB is at the forefront of this evolution.

1 Residential applications are characterized by a poor match between the energy demand profile over the day and the solar energy production curve.



For years in the residential arena, the FIT scheme ensured remuneration for every solar kWh injected into the grid at a tariff substantially higher than the retail electricity price – without requiring a match between what was injected and the actual demand of the household, either in terms of energy balance or in terms of power equivalence at any given time. This is changing. This landscape is now evolving from a form of financial investment into the fulfillment of a fundamental need and is largely driven by the following factors: the potential grid instability issues as a result of increased penetration of distributed generation, the approaching parity of self-generation costs and retail energy costs, and the reduction of incentives.

By paving the way for the dispatchability of solar power and the optimization of locally generated power, which result in grid-integration and energy cost reductions, respectively, energy storage will drive the next generation of PV systems. While the containment of grid integration costs is a priority for utilities, the

energy cost reduction will help bring PV systems more easily into the home.

Self-consumption and self-sufficiency

There are two governing factors for the next generation of residential solar solutions: energy self-consumption and energy self-sufficiency. Energy self-consumption is the household consumption of the solar energy locally produced and energy self-sufficiency is the capability to autonomously meet the energy demand of the household. The next generation of solar systems are expected to both supply electric power to the household according to demand and minimize the purchase of electricity from the grid. In order to meet these two requirements, the mismatch between the daily solar power profile and the household demand must be overcome → 1.

There are several ways in which an acceptable level of self-sufficiency and self-consumption in residential solar applications can be achieved:

- Load management of home appliances by shifting their use to daytime, when the solar energy is present.
- Storage of the energy available from the source (whenever it exceeds the household demand) and delivery of

the energy when it is needed, often before sunrise and after sunset.

- Adoption of electrical loads to replace more traditional, nonelectrical solutions such as thermal loads and/or electric vehicles.
- Aggregation of the local energy management system to larger grid-coupled distributed systems for provision of ancillary services.

Solar as we have known it will likely look decidedly different in the future – especially in the residential arena – and ABB is at the forefront of this evolution.

A level of self-consumption and self-sufficiency that exceeds the threshold of 30 percent each – usually achievable by traditional PV plants – can only be cost-effectively obtained through a combination of all or part of the above solutions. For the implementation at the product level, the two pursuable solutions are load management and energy storage.

Energy storage in residential solar applications

Electrochemical batteries are one of the best ways to store excess solar energy because they are practical and cost-effective. However, while the arbitrary addition of batteries to a PV plant could help achieve complete self-sufficiency of the household, it might not result in a

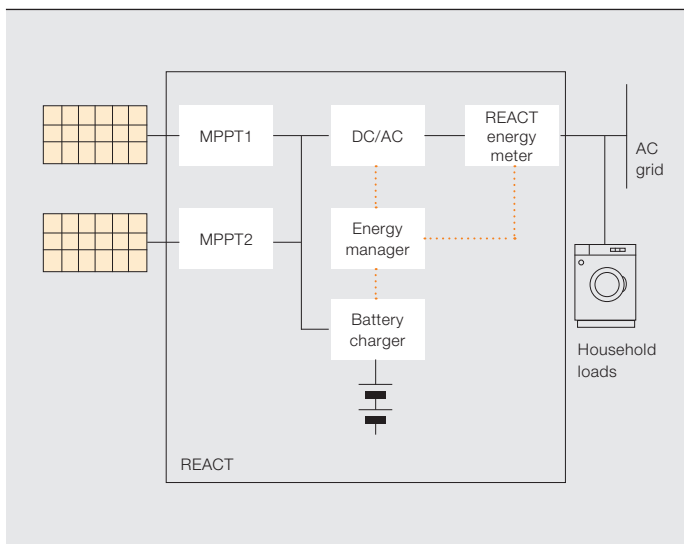
Title picture

How can ABB's residential energy storage solutions help lead the way for more flexible and accessible solar PV installations in the home?

2 ABB's REACT (Renewable Energy Accumulator and Conversion Technology)



3 Block diagram of REACT. The system features a dedicated energy meter for self-consumption and self-sufficiency control.



positive financial return. This is due to the current high cost of technically viable solutions for batteries along with the necessary oversizing of the PV array required to charge the battery.

An economically sustainable residential PV/storage solution is instead the result of a compromise between the size of the installed battery and the returns achieved by self-consumption and self-sufficiency levels as a part of an overall tailored energy management strategy. In other words, it is all about the optimum trade-off between the cost of the battery (and the size of the PV array) and the reduction of energy purchased from the grid that the system can achieve.

ABB's REACT (Renewable Energy Accumulator and Conversion Technology) is designed to offer customers the above-mentioned optimum trade-off → 2. The system is made of a grid-tied PV inverter (up to 5 kW) fed from a DC link, to which the maximum power point trackers (MPPTs), connected to the PV array, and a bidirectional battery charger are connected → 3.

Its integrated DC-link architecture provides the optimum cost solution for new installations, and it can also be used to retrofit existing PV plants as an AC-link

battery charger simply by not connecting the PV array to its input → 4.

REACT features a modular architecture with the electronics compartment on the right side and the battery compartment on the left. Up to three battery compartments can be installed in one system. The product offers battery backup functionality in the event of a grid blackout.

Effectiveness of product implementation

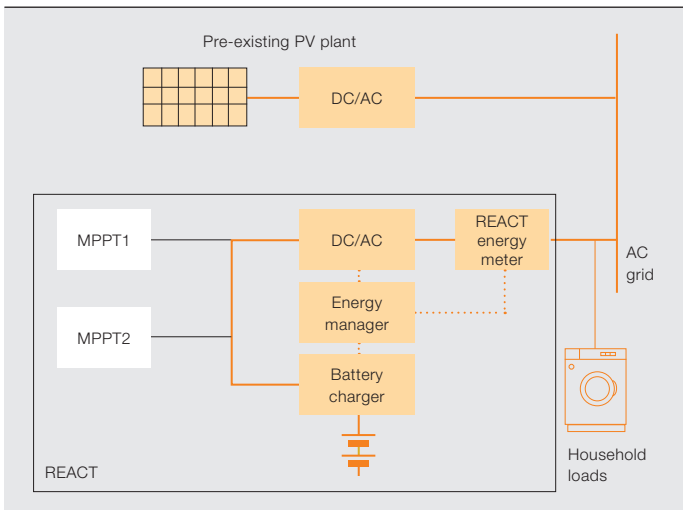
REACT's energy storage system is made of lithium-ion batteries with a modular architecture that allows the system to expand from its native 2 kWh up to 6 kWh, and is field upgradable. An effective onboard load management system enables interaction with selected loads/appliances, boosting the energy independency of the household up

The next generation of solar systems are expected to both supply electric power to the household according to demand and minimize the purchase of electricity from the grid.

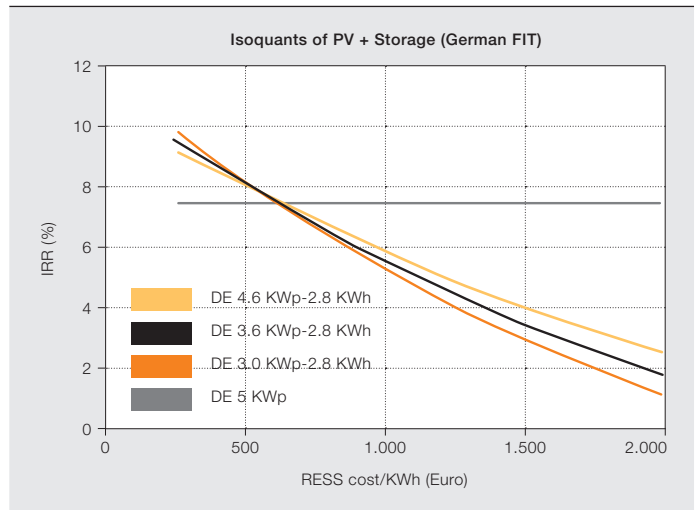
to 60 percent with a basic system configuration → 5. The trade-off between the size of the battery and the level of self-sufficiency offered by the system is

There are two governing factors for the next generation of residential solar solutions: energy self-consumption and energy self-sufficiency.

4 Retrofit of a pre-existing PV plant with REACT in AC-link mode.
The PV inputs of the REACT (MPPT1/2) are not used.



5 IRR of a PV+ storage residential system (German case) by system configuration versus the cost of the battery system.



a moving target driven by the cost of batteries over time. The extension of the battery capacity up to 6kW is therefore possible for post-installation system scale-up when the cost of batteries allows a better internal rate of return (IRR) of the system → 5.

The addition of energy storage capability to a traditional solar inverter represents the evolution of solar residential systems toward self-sustainability.

Business case example

The choice of lithium-ion batteries as the storage element is driven by:

- The favorable expected cost profile in the coming years → 6.
- Size/capacity and performance
- The charge/discharge power rating (0.5xC to C is achievable without negative impact on the life of the battery)
- Twice the longevity (10 years)
- Efficiency (discharge vs. charge energy) over 95 percent

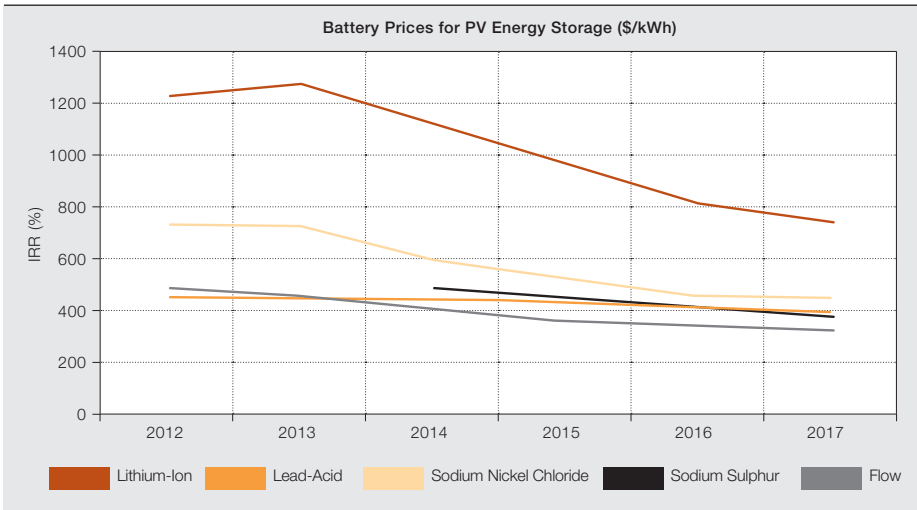
→ 7 shows the result simulated for a household in Munich, Germany, under the following assumptions:

- Annual solar production 990 kWh/kWpeak
- Family of four
- Annual consumption of 4,100 kWh (refrigerator/ freezer: 0.4 kW; washer: 2.0 kW; heat pump: 2.0 kW; electric oven: 2.8 kW)
- Installed PV capacity 5 kWDC
- Retail electricity cost 0.23 euros/kWh (\$.26/kWh)

The addition of a 2 kWh storage component to a 5 kW residential plant can boost the self-sufficiency and self-consumption of this typical household by 15 and 10 percent, respectively. An even further improvement of 5 to 7 percent can be achieved by adding another component to the system – the home load management → 7.

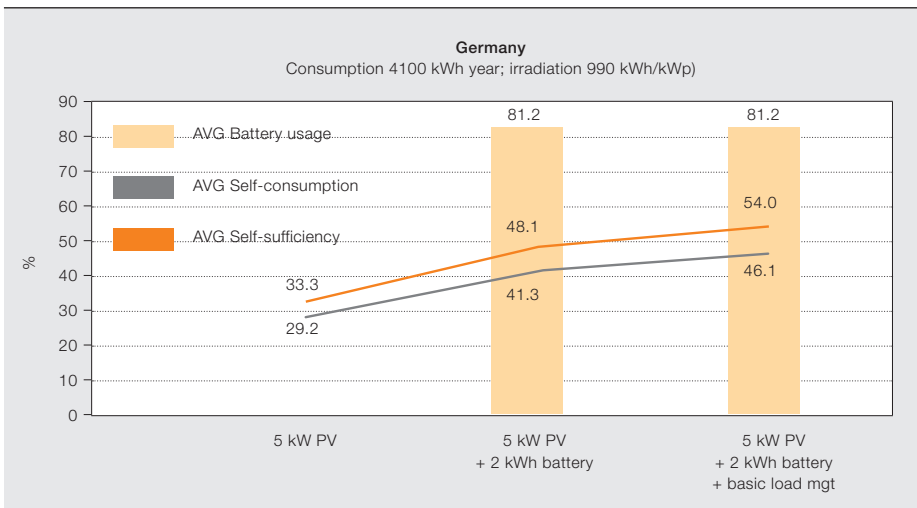
The home load manager operates a shift of the household power demand by interacting with noncritical, programmable appliances. Given the microprocessor control in most of today's large appliances, the ideal interaction with the home load manager would be through a data link connecting the home loads to the load manager. This communication standard, while widely deployed by appliance manufacturers and being addressed by several committees in Europe and the United States, has unfortunately not yet been recognized and implemented. Therefore the effective way to integrate the load manager into REACT is through a series of signals used either to power the programmable loads or to sug-

6 Expected cost trend by battery technology. Lithium-ion shows the stronger reduction of cost coupled with one of the longest battery field life. Source: IMS



The addition of energy storage to solar will drive the next generation of PV systems.

7 Level of self-consumption and self-sufficiency achieved in typical installations in Germany with different levels of PV system configuration.



gest to the operator when a certain load should be started.

At any rate, REACT is full home automation ready with the possibility to interface with the household's critical loads and even an external energy manager system through the upcoming communication standards on digital link, Wi-Fi or ZigBee.

Solar residential systems evolve

The addition of energy storage capability to a traditional solar inverter represents the evolution of solar residential systems toward self-sustainability. In order to achieve a positive return on investment, it is critical to maintain a proper trade-off between the cost of batteries and the level of energy self-sufficiency/consumption.

A careful selection of the size of the battery must be supported by the deployment of an effective strategy to manage the system's energy flows: from the PV source to the battery, to and from the grid and to the household's appliances, and some level of interaction between the inverter's energy manager and the house's loads. As the business case illustrates, ABB is poised to offer a complete residential energy storage solution, with the latest load management technology, that will lead the way for more practical and flexible solar PV installations in the home.

Paolo Casini
 ABB Discrete Automation and Motion,
 Power Conversion
 Terranuova Bracciolini, Italy
 paolo.casini@it.abb.com



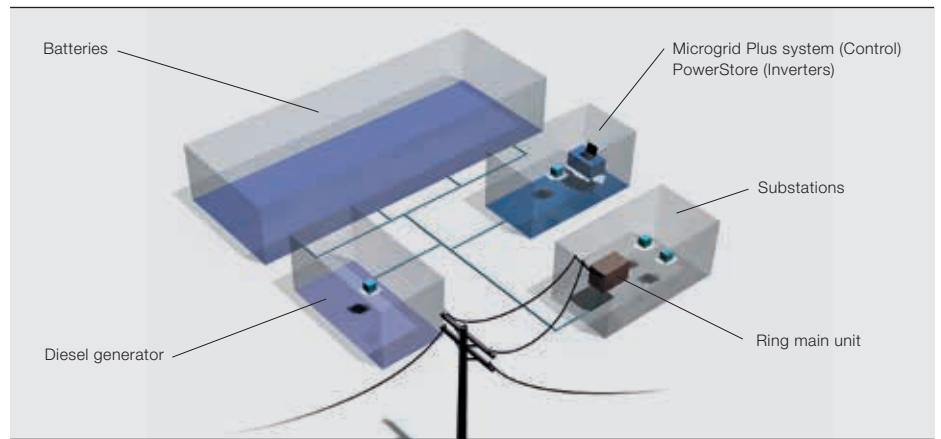
Unlocking value in storage systems

A large-scale case study of a battery/diesel
grid-connected microgrid

NIRUPA CHANDER, JACK GAYNOR – Much progress has been made in the field of large-scale battery technology. As this technical evolution gathers pace, it creates economies of scale that make the technology ever more commercially attractive. This technical advance and changing cost landscape have led many industrial utilities to investigate the use of battery technology as the basis for a grid energy storage system (GESS). Based in Victoria, Australia, AusNet Services began investigating the GESS

concept in 2013 and quickly decided to start a trial aimed at exploring the technology's potential to manage peak demand and defer investment in network upgrades. Through a competitive tender process, AusNet Services awarded the contract to design, construct and deliver a GESS to a consortium led by ABB and Samsung SDI, with ABB providing the integration technology and design, and Samsung SDI taking the role of battery supplier.

1 System overview



System outline

The GESS consists of three main components: A 1 MWh 1C (the “C” refers to charge/discharge performance) lithium-ion battery energy storage system coupled to the grid through a 1 MVA inverter; a 1 MVA backup diesel generator; and a grid-connection substation consisting of a 3 MVA transformer and a sulfur hexafluoride (SF₆)-filled ring main unit (RMU) and power protection devices → 1. All the system components are portable, with the generator, batteries and a PowerStore™ 4Q (four-quadrant) PCS100 inverter housed in shipping containers equipped with integrated HVAC (heating, ventilation and air-conditioning) and fire suppression. The transformer and RMU are housed on skid-mounted platforms.

The Samsung SDI battery system consists of four self-contained shipping containers. The 1 MWh 1C batteries are capable of symmetric charge and discharge ratings of ±1 MW and can transition from charge to discharge very quickly, allowing for robust operation.

ABB PowerStore

The heart of the GESS is the ABB PowerStore IGBT (insulated-gate bipolar transistor)-based 4Q PCS100 inverter that interfaces the Samsung lithium-ion battery energy storage system to the grid through a 1,000V DC bus. With a symmetric power rating of ±1,372 kVA, PowerStore provides fully bidirectional

real and reactive power management. In the GESS, PowerStore operates in virtual generator mode (VGM) as a voltage source inverter functioning as a synthetic generator. This is rather like a traditional diesel generator but with exceptional response time, and expanded power supply and stability capabilities – similar in effect to a STATCOM (static compensator). This enables PowerStore to act as a grid-forming generation source that other synchronous generators, such as wind turbines or solar inverters, can use as a network voltage and frequency reference. Additionally, PowerStore responds

An embedded generation source such as a GESS can provide peak load support by supplying upstream feeder loads locally during peak consumption periods.

to faults in the network in the same way as a synchronous generator, supplying up to 2 pu (per-unit) fault current for 2 s.

A 1 MVA diesel generator is supplied to extend the discharge duration and power output of the GESS, recharge low batteries and provide power to the microgrid.

Both PowerStore and the generator are interfaced to the 22 kV grid through a 3 MVA transformer with a primary-connected neutral switch and a three-breaker SF₆-filled RMU. Power protection intelligent electronic devices (IEDs) – three ABB REF630s – protect and monitor the

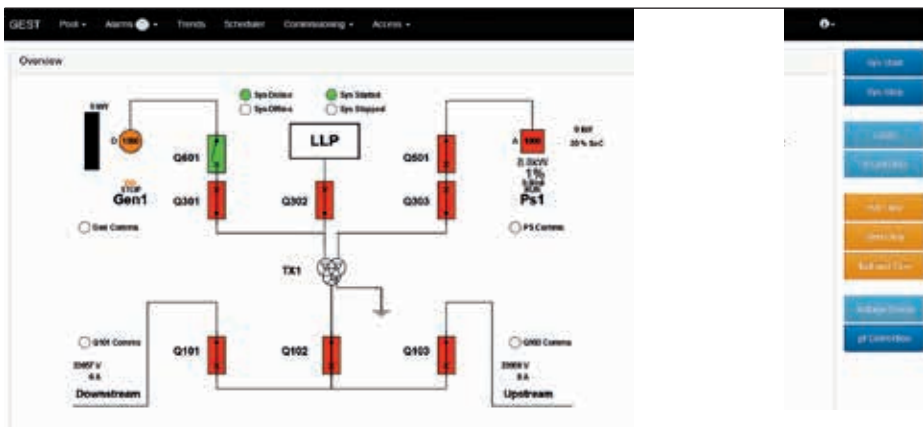
Driven by interested parties as varied as power utilities, automobile manufacturers and data center operators, battery technology has advanced remarkably in the past decade. In tandem, new battery applications have grown in number. Of particular interest is the use of grid-connected large-scale battery microgrids to manage peak demand and defer network augmentation. It was chiefly to investigate these two aspects that AusNet Services carried out a trial of a non-network GESS. The company chose a consortium led by ABB and Samsung SDI to deliver the GESS. Given the capabilities of the GESS with regard to power quality, the effect on local power quality and stability of using such an embedded generator was also to be examined. Additionally, the potential of the GESS’s islanding capabilities to improve power supply and stability in the case of larger network faults was to be explored.

Title picture

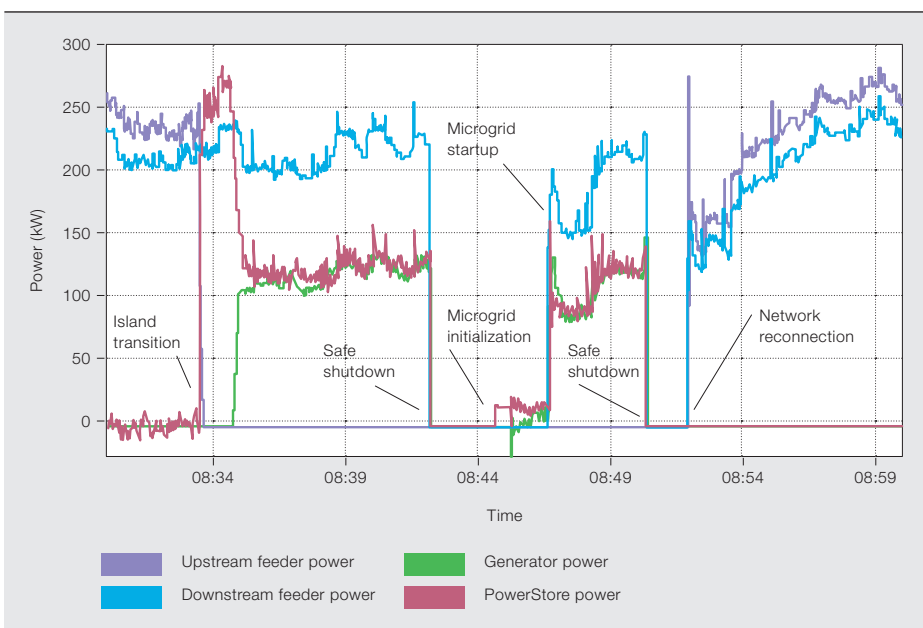
ABB led the delivery of a large-scale battery installation (shown) for AusNet Services in northern Melbourne, Victoria, Australia. How has it helped the utility manage demand and optimize investment?

The GESS allows the downstream system to operate as an islanded microgrid – supplied wholly by the GESS – or as a grid-connected system.

2 GESS M+ Operations overview screen



3 GESS island mode operation: transition from grid connection to islanded microgrid, microgrid system shutdown, microgrid initialization and network reconnection



grid connection. An ABB Synchrotact® allows the GESS to synchronize with the grid and transition from islanded operation to grid-connected mode via “bumpless” transitions. If local power is lost, the GESS can supply the 240V AC auxiliary control network for at least 8 h.

Microgrid Plus control

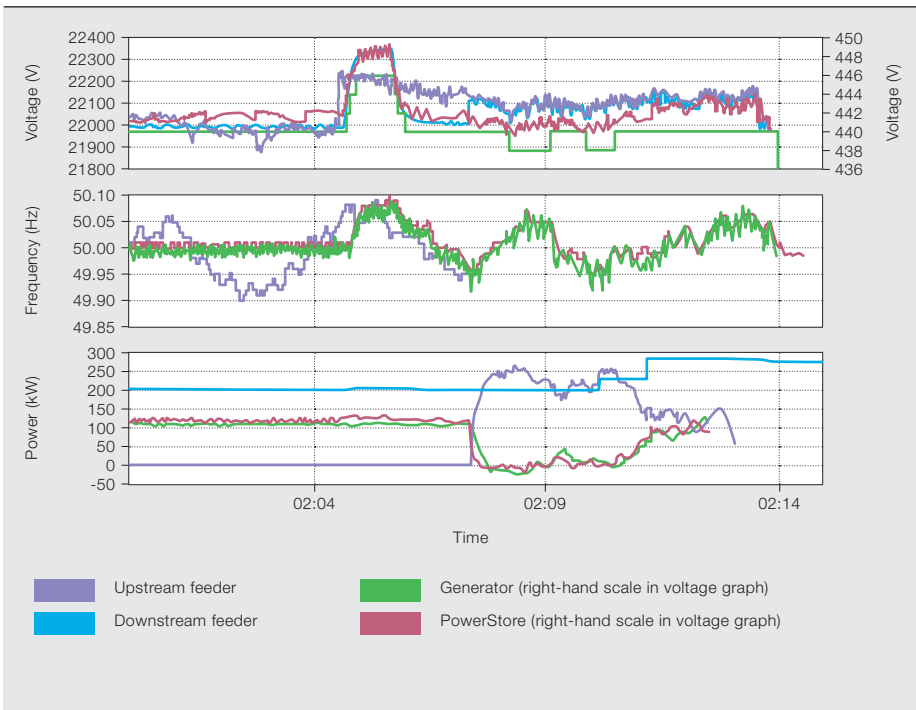
ABB’s Microgrid Plus control system manages the GESS and ensures that consistent grid supply and stability is maintained. This distributed control system interfaces to each major piece of plant, from which it collects power system information to publish to the entire network. Individual Microgrid Plus controllers act in a distributed manner, resulting in the entire GESS performing as a cohesive whole. Remote monitoring and management is provided through ABB’s M+ Operations and also through a

remote terminal unit (RTU) connection to the AusNet Services control system → 2. Spinning reserve is maintained by the Microgrid Plus control system by constantly monitoring power and energy flows to ensure that any required load steps can be accommodated.

GESS protection

Protection is ensured by using a set of complementary methods. The Samsung BMS communicates any alarms to the Microgrid Plus control system, which, in turn, will cease operation in the event of a critical alarm. Anti-islanding protection is implemented to ensure that, in the event of an upstream feeder opening, the GESS does not attempt to supply to the wider distribution network or grid of which this feeder is a part.

4 GESS synchronization: voltage, power and frequency during transition and synchronization from islanded to grid-connected using a load bank



When the network voltage is above the set point, the GESS absorbs reactive power; when below, the GESS injects reactive power into the network.

Various power system protection functions are implemented by REF630 relays, a backup sensitive earth fault relay and insulation monitoring relays.

Island mode

When transitioning from grid-connected mode to island mode, the GESS increases its power output so that the power flow across the upstream breaker is zero and the GESS is supplying the entire downstream feeder load as well as the auxiliary power load (hence the ~30 kW difference between the PowerStore power and downstream feeder power and between upstream feeder power and downstream feeder power) → 3.

With the power flow across the upstream breaker zero, the breaker opened and PowerStore alone supplying the microgrid, the generator is started and PowerStore and the generator passively load share the downstream feeder load until a safe system shutdown is performed. Then, when initializing the microgrid, PowerStore starts to provide a system reference for the generator to synchronize to, and then the downstream feeder breaker is closed and the GESS supplies the downstream feeder until another safe system shutdown is performed.

When the generation sources change state from online to offline, and vice versa, the IED protection groups are changed automatically, thus ensuring the REF630 IEDs use the correct protection settings.

When transitioning to a grid-connected system and back again, the GESS adjusts the voltage and frequency output of PowerStore and the generator to ensure that the downstream feeder voltage and frequency are equal to those of the upstream network → 4. This is accomplished by an ABB Synchrotact sending signals to the Microgrid Plus control system, which then adjusts the output voltage and frequency of PowerStore and the generator to synchronize the two networks. The transition back to an islanded state is as described above: When the power flow across the upstream breaker is zero, the upstream breaker is opened and the high-voltage neutral switch is closed.

Lopping, injecting and correcting

When performing peak lopping (ie, using GESS to remove demand peaks on the primary power supply), the Microgrid Plus control system injects power from

PowerStore or the generator to maintain the upstream feeder load at a predetermined maximum power set point while meeting the downstream feeder requirement → 5. When PowerStore and the generator are both online they passively and proportionally share the power load requirement.

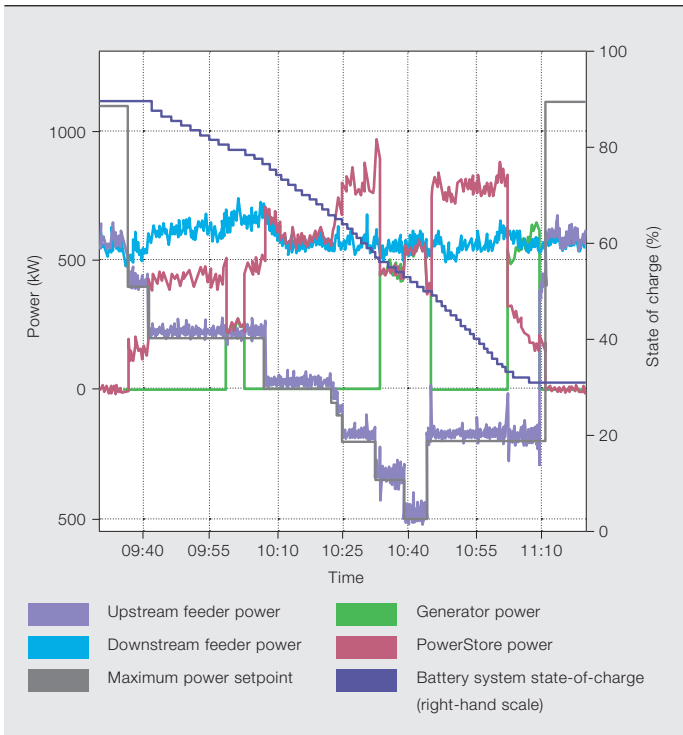
When the state-of-charge of the batteries reaches a minimum set point (35 per-

A GESS helps mitigate the supply and stability issues associated with renewable intermittency.

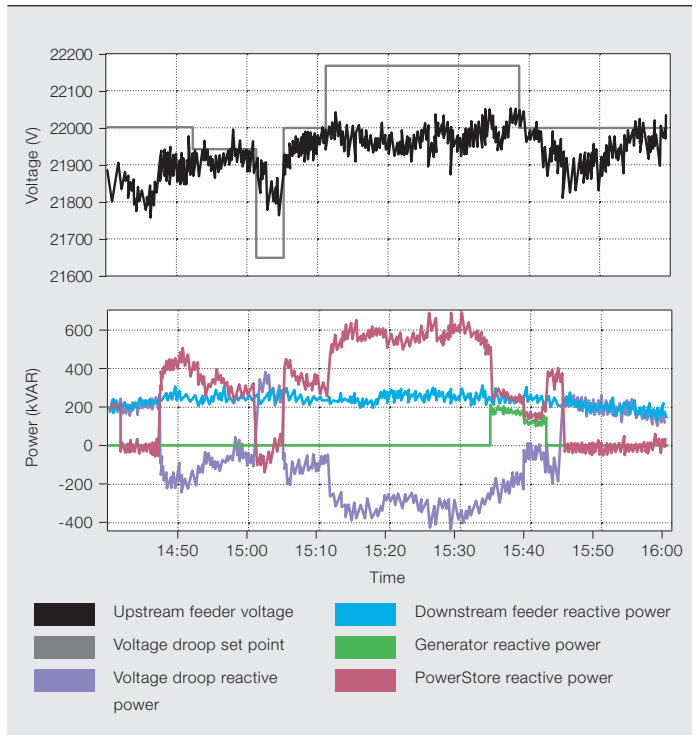
cent in → 5), the microgrid increases generator loading and reduces PowerStore loading to reduce the discharge rate.

When operating in voltage droop mode, the system compares the network voltage to a set parameter with the difference between the two values being used to determine the amount of reactive power to be injected into or absorbed from the grid in order to stabilize the network voltage → 6.

5 GESS peak lopping



6 GESS parameters during voltage droop



Power factor correction is performed by injecting reactive power into the network, or absorbing reactive power from it, in a manner similar to that employed by the voltage droop algorithm.

Charging at minimum feeder load charges the battery while also meeting the downstream feeder load requirements. When the upstream feeder demand is greater than the maximum set point, the GESS performs peak lopping as described above. Timed charging can be used to charge the batteries when energy cost is low.

System outcomes

Encouraging results from the trial support the GESS as a product that will strengthen and stabilize the power grid while enabling power system upgrades to be postponed or eliminated. The islanding capabilities of the GESS will help reduce the severity and duration of outages in larger macrogrids as serious faults can be isolated and rectified while the supply to interrupted areas is maintained by the GESS. A compact, portable design allows the GESS to be positioned near the customer's site.

Battery-based energy storage systems show promise for increasing the contribution of solar generation to larger traditional macrogrids as the intermittent nature of

solar sources can be smoothed by a GESS or similar. Indeed, a GESS could be used to support any distributed generation sources.

Advances in lithium-ion battery technology – especially with charge and discharge ratings approaching 4C (whereby a 250 kWh battery bank would be able to discharge at 1 MW) and the footprint becoming smaller – open up exciting possibilities for cost-effective energy storage in smaller, more remote microgrids. Increased ratings are also attractive in larger grid-connected systems for local intense peak load support, such as that needed to support arc furnaces, large cranes, hoists and other large, intermittent industrial loads.

ABB and Samsung SDI plan to continue to develop modular and scalable energy storage systems for use in microgrids and other applications, and will continue to explore how such technologies can enable customers to reduce their environmental impact and increase stable and sustainable renewable contributions to their grids.

For their valuable contributions, the authors would like to give special thanks to Yogendra Vashishtha, AusNet Services project manager, and Hachull Chung, Samsung SDI project manager.

Nirupa Chander

ABB Power Grids, Grid Automation
Notting Hill, Australia
nirupa.chander@au.abb.com

Jack Gaynor

Former ABB employee

Editorial Board

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Head of Corporate Communications

Ernst Scholtz

R&D Strategy Manager
Group R&D and Technology

Andreas Moglestue

Chief Editor, ABB Review
andreas.moglestue@ch.abb.com

Publisher

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ABB Review
Segelhofstrasse 1K
CH-5405 Baden-Daettwil
Switzerland
abb.review@ch.abb.com

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Transportation

The increased globalization of processes and services relies on the ability of people and goods to be moved – be it goods being sent half way around the globe on a large ship, or workers on their daily commute within a city using electric cars, buses or trains. ABB believes transportation systems should be respectful of the environment, sustainable on resources and also economically competitive. ABB provides numerous cutting edge services and products supporting the transportation industry. These range from the propulsion system of large ships to charging stations for electric cars. Besides the actual hardware it increasingly encompasses service and remote service offerings.

Transportation, and ABB's contribution to it will be the main focus of the upcoming issue of ABB Review.



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Our contribution to the future: running the world without consuming the earth.

To change the world, you need a pioneering spirit and ground-breaking innovations. That's what Solar Impulse found in ABB. Our collective vision is clear: running the world without consuming the earth. As a pioneering technology leader, it's something we've always done in the fields of renewable energy, energy efficiency and sustainable mobility. Solar Impulse has taken this message to new heights. For ABB the journey continues. Digitization and sustainability are integral parts of a fourth industrial revolution, and ABB will lead the way – powered by innovation. To follow this story, visit www.abb.com/betterworld

