ABB review

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The corporate technical journal

A century of *ABB Review*

Power and productivity for a better world™

Dear Reader,

Technological innovation has been the cornerstone of ABB's success since the founding of our predecessor companies in the late 19th century.

Today, we invest $1.5 billion each year in R&D and we have 8,500 technologists focused on power and automation innovations around the world.

For 100 years, *ABB Review* has been keeping our shareholders, customers and employees informed about our innovative solutions and achievements in the areas of power and automation.

Just like ABB, *ABB Review* is continually innovating in terms of content and design.

The next phase of *ABB Review* will be to strengthen its presence online to meet the opportunities and demands of the digital world, for instance through more interactive communication.

We are proud to share our centenary issue with you.

Ulrich Spiesshofer
Chief Executive Officer
ABB Group

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Knowledge to power

Power is knowledge

100 years of *ABB Review*

Claes Rytoft

Dear Reader,

History often holds the key to understanding the present. Its study can at times humblingly reveal that ideas we erroneously classify as recent have been around for much longer than we imagine. On the other hand it can upliftingly remind us how quickly breakthroughs can totally transform large parts of the industry.

2014 is a year of several landmark anniversaries for ABB. As you have probably gathered from the cover of this edition, *ABB Review* is 100 years old this year. We are marking the anniversary by dedicating an entire section to the centenary (and are also planning other events during the course of 2014).

A single issue of *ABB Review* is insufficient to even skim the surface of the wealth of material available in the archives. We hope, nevertheless, that our small selection will give you a taste of the breadth of development the journal witnessed in its long history. For reasons of space, even these few selected articles had to be shortened in the print edition, but readers of the tablet version of can enjoy them in full length.

The two other great anniversaries of this year relate to robotics and HVDC. Forty years ago, in 1974, ASEA launched the IRB 6, the world's first commercially available microprocessor-controlled and all-electric robot. Virtually all industrial robots in use today fall into this category while also taking up the IRB 6's anthropomorphic configuration.

Sixty years ago, ASEA delivered the world's first commercial HVDC link, transmitting power from the Swedish mainland to the island of Gotland. The line delivered 20 MW over 98 km at 100 kV. These figures may appear but small fry compared to later HVDC projects, but this pioneering link was trendsetting in more respects than one: Its underwater cables, for example, also introduced concepts still valid today.

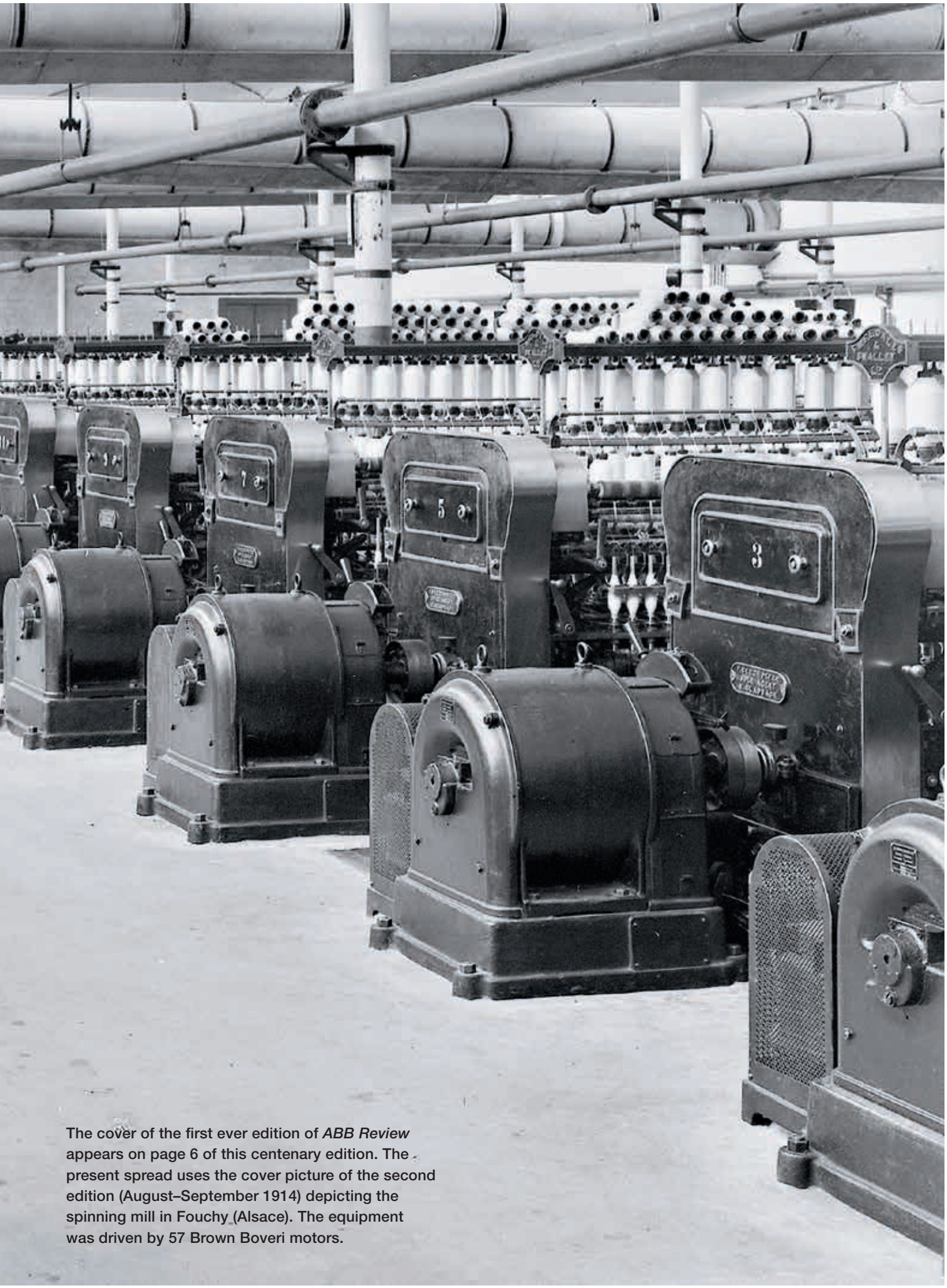
Both of these anniversaries are covered by dedicated articles in this issue.

Further articles cover trends in fields as varied as pumped storage, motor design, power electronics, sensors, UPS and simulation.

I trust that this anniversary edition of *ABB Review* with its insights of past, present and future developments will inspire you (as it did us) in the discovery and rediscovery of both known and unknown sides of ABB.

Enjoy your reading.

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

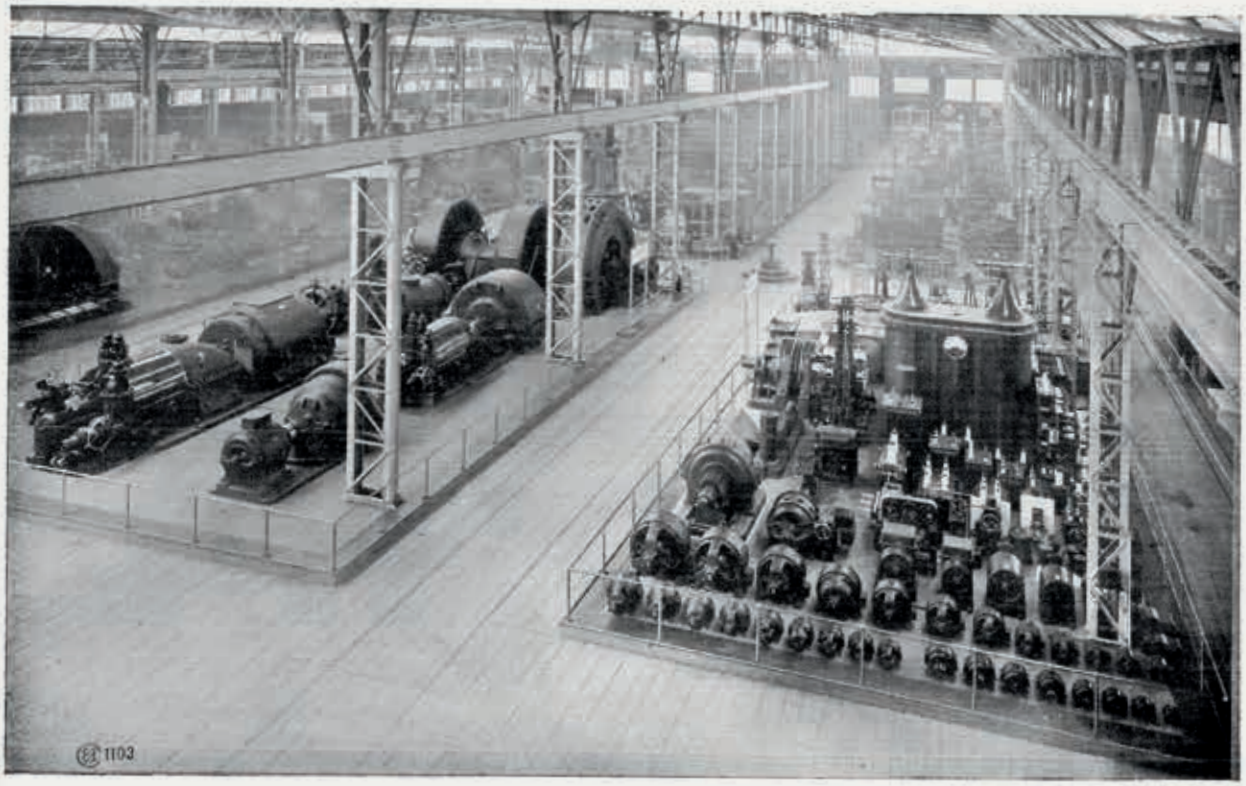


The cover of the first ever edition of *ABB Review* appears on page 6 of this centenary edition. The present spread uses the cover picture of the second edition (August–September 1914) depicting the spinning mill in Fouchy (Alsace). The equipment was driven by 57 Brown Boveri motors.

1ère ANNÉE. No. 1, JUILLET 1914.

REVUE BBC

Publiée par la Société Anonyme BROWN, BOVERI & Cie., à BADEN (Suisse)



Les stands BBC dans la galerie des machines de l'Exposition Nationale Suisse, à Berne.

SOMMAIRE:

100 years of *ABB Review*

Looking back on a century in print

ANDREAS MOGLESTUE – History is more than the recording of chronology. Although the great milestones of political change, of wars and of landmark achievements may form the skeletal backbone of history, what breathes life and context into our understanding of the past are the smaller events that are handed down to us: the memories, photographs, facts about everyday life and objects that each tell a story. Much of the great fascination in looking back over *ABB Review*'s 100 years lies in the latter.

1914

ABB Review's predecessor journal, *BBC Review*[1], was first published in July 1914. Its initial purpose was to inform sales agents and business partners of the company's products, developments and activities. In later years, distribution grew to encompass a broader readership including customers and suppliers, consultants and journalists as well as universities, educators, students and lay people with an interest in technology. Many engineers who later came to work for ABB began to read *ABB Review* in their student days and were inspired in their career choice by the company's technological prowess. Similarly, many trade journals regularly publish articles that were first seen on the pages of *ABB Review,* and illustrations and diagrams from its pages have been republished in university text books. Part of the journal's appeal lies in its aim to be as objective as possible: Although it clearly speaks from an ABB perspective, *ABB Review* strives to remain factual and unbiased in the claims it makes.

Over the last 100 years, the pages of *ABB Review* have featured a staggering number of contributions on a broad range of subjects. Some articles covered the predecessors of products still manufactured by ABB. Many of the statements made in these articles are still surprisingly valid today. Other contributions reflect developments that were not pursued further by the company or that developed in a different way than expected.

Besides documenting this progress, the archives also present other insights. The style of publication has clearly developed over time – not just in terms of the development of typography, the gradual intro-

Title picture
This was the cover of the first-ever edition of *BBC Review*. The photograph depicts the Swiss National Exhibition held between May and October 1914 in Bern (Switzerland).

Footnote
1 Although BBC's full name was "Brown, Boveri & Company," the journal was spelled wihout the comma – *The Brown Boveri Review*.

1914 – ***BBC Review* published for the first time**; Panama Canal is officially opened

1918 – *Reader's Digest* is launched

1921 – Women achieve equal voting rights in Sweden

1922 – Insulin hormone is isolated by Sir Frederick Grant Banting

1923 – First publication of TIME magazine

duction of color photographs or questions of style or presentation, but also in the manner in which articles are presented. Early issues make more liberal use of mathematical proofs, detailed circuit diagrams and construction drawings than is the case today. This may on the one hand be driven by concerns over the need to protect intellectual property, but also by changed reader expectations and subtle changes in the positioning of the journal.

BBC's sister company, ASEA (with which it merged in 1988 to form ABB) had its own publication, *ASEA Journal*. The latter was some years older than *BBC Review,* having first appeared in 1909. The company merger also led to a merging of the two editorial offices and *ABB Review* builds on the traditions of both predecessor journals.

Today, *ABB Review* is distributed to more than countries and published in five languages. Almost 60,000 copies of every edition are printed. There is furthermore a growing electronic distribution, both using a "classical" pdf format and more advanced tablet versions for iOS and Android.

Space constraints mean that the historical clippings presented in the following pages must appear in a much abridged form in the print and pdf versions. The tablet version contains more extensive versions of some of the items.

Andreas Moglestue
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Remembering the founders

Charles Eugene Lancelot Brown and Walter Boveri jointly founded BBC on October 2, 1891. Although both men came from an engineering background, Boveri grew increasingly active in the stewardship and growth of the company whereas Brown continued to focus on engineering challenges. Their names are remembered today in the two Bs of ABB. Both men passed away in 1924. As far as the editorial team can ascertain, theirs were the only obituaries ever to have been published on the pages of this journal.

The founders of ASEA, Ludwig Fredholm and Jonas Wenström passed away in 1891 and 1893 respectively, before the birth of the *ASEA Journal*.

The death of C. E. L. Brown, which took place at Montagnola near Lugano on the morning of May 2nd after a brief illness, marks the passing of a figure which had already become almost legendary in the world of electrical engineering. This is partly accounted for by the fact that Brown retired from active participation in electrical affairs thirteen years ago, but is, perhaps, to a great extent due to the attitude of a younger generation, which takes for granted the achievements of the past and, striving onwards, finds but little leisure for considering pioneer work carried out before its time. Thus, there is a tendency to forget to whose genius we owe so much of the progress which has been made in the design and construction of electrical machinery.

Charles Eugene Lancelot Brown was born at Winterthur in Switzerland on June 17th, 1863, the son of Charles Brown, an engineer well known as the originator of the bayonet-type frame and the Sulzer drop-valve steam engine. After one year's apprenticeship with M. Burgin in Basle, he was engaged in the spring of 1885, when hardly 22 years old, by the Oerlikon Engineering Works, and two years later was put in control of the electrical department. This marks the commencement of an exceptionally fruitful career.

During his first years with the Oerlikon Company, Brown devoted his energies to the development of the direct-current system, and particularly to the production of practical direct-current machines.

But a few months have elapsed since we recorded the death of the genial inventor and designer C. E. L. Brown, and now his nearest colleague and the co-founder of our firm, Walter Boveri, has followed him on the last journey. His passing away has deprived the Swiss electrical industry of its most outstanding personality, and no deeper loss could have been sustained.

W. Boveri was born in Bamberg in the year 1865, and after a course of engineering training at Nuremberg, he came to Switzerland when 20 years of age. Here he entered the Oerlikon Engineering Works, where, under the direction of C. E. L. Brown, the manufacture of electrical machinery was just being undertaken. Boveri, who subsequently took charge of their erection department, assisted throughout the development of the direct-current machine there, and in the year 1888 carried out the erection and setting into operation of the first electric power transmission scheme from Kriegstetten to Solothurn. In 1891, after a period of six years with the Oerlikon Company, he and C. E. L. Brown, with whom he was closely associated, founded the firm of Brown, Boveri & Co. at Baden.

In the early years following the foundation of the firm, Boveri devoted himself, as at Oerlikon, to the planning, installation, and putting into operation of both small and large plants. The unusually good results obtained with Brown's designs, however, soon resulted in a very rapid increase in the activity of the Baden works, and it was not long before Boveri was faced with work of a very different nature. The pro-

1924

1924

Death of Charles E.L. Brown, cofounder of BBC

Death of Walter Boveri, cofounder of BBC

First winter Olympics

1925

John Logie Baird demonstrates television

1928

Flying Doctor service starts in Australia

1931

Opening of the Empire State Building in New York

1935

First night game in Major League Baseball made possible by electric lighting

The Hollerith machine

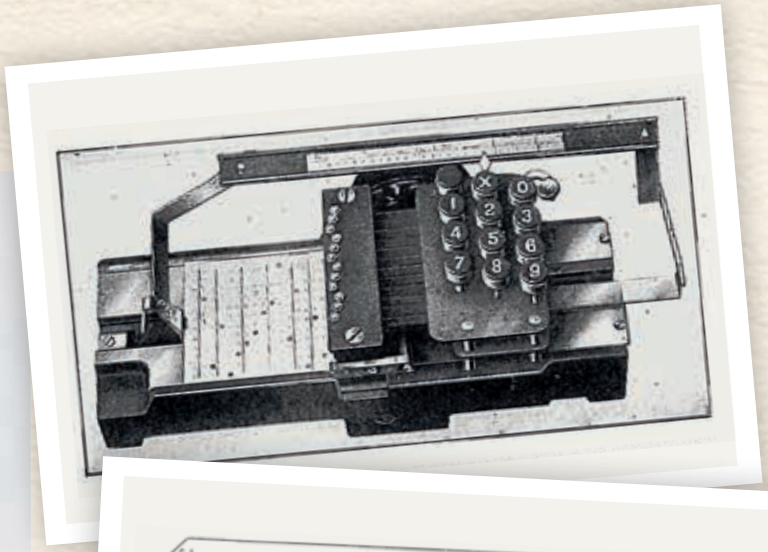
The Hollerith classification system permitted the automatic compilation of statistics. Data were stored by punching holes in cards. Counters were triggered by electrical connections. Herman Hollerith's machines were used in the 1890 US census, permitting the counting to be completed in a year (the previous 1880 census had taken eight years). The Hollerith machine can be considered an early computer.

Hollerith's invention was initially patented, but because of its universal significance in improving the handling of data, the US government removed this restriction in 1910. BBC was one of the companies to benefit from this.

Punched cards were first introduced in the 18th century and used to "program" textile looms and musical machines. Later they were used for data storage and the programming of computers.

It is interesting to observe that today's DVDs still rely on microscopic holes to store data.

The Brown Boveri Review, November – December 1914



Throughout its long history, ABB has equipped countless power plants, many of which are still generating electricity today. This one is in Peru's Santa Eulalia Valley.

The Brown Boveri Review, October 1939

THE BROWN BOVERI REVIEW

THE HOUSE JOURNAL OF BROWN, BOVERI & COMPANY, LIMITED, BADEN (SWITZERLAND)

VOL. XXVI OCTOBER, 1939 No. 10

The Brown Boveri Review is issued monthly. — Reproduction of articles or illustrations is permitted subject to full acknowledgment.

JUAN CAROSIO, A BIG MODERN HYDRO-ELECTRIC POWER STATION IN PERU.

Decimal Index 621.283.21 (85).

A description is given, here, of the design of the generators and transformers and of the layout of the switchgear of the new Juan Carosio hydro-electric power station in Peru. Further, details are given of the protective and regulating devices for the machines and the network and a description of the auxiliary devices of the power station.

A new hydro-electric high-head plant of 3 × 17,150 H.P. output (Fig. 1) has been built by the Empresas Eléctricas Asociadas, Lima, in the Santa Eulalia valley, at 1400 m above sea level and at about 60 km from the town of Lima. This is one of the biggest hydro-electric power stations built, so far, in South America. Thanks to their wide experience in hydro-electric station work, Brown Boveri were given the order for the entire electric equipment. The power station conforms to the very latest conceptions in power plant design, oil being eliminated as far as possible as an insulating agent in apparatus; air-blast circuit breakers and bushing current transformers being put in, to this end. Further, special measures have been taken to facilitate service and supervision by making use of a light diagram and by using electro-pneumatic remote control of circuit breakers and disconnecting switches as well as effective protective and regulating devices and extensive automaticity of the auxiliary services. Since the spring of 1938, this plant has been running to the entire satisfaction of the clients, allowing the Empresas Eléctricas Asociadas to stop the Lima steam power station, entirely, and keep it as a stand-by and peak-load plant.

Fig. 1. — External view of the Juan Carosio hydro-electric power station, in Peru.

I. LAYOUT OF THE PLANT.

Fig. 2 gives the fundamental diagram of connections of the electrical part. There are three generator-transformer sets each of 17,500 kVA, working directly on a double set of 64-kV bus-bars. From these, 5 high-voltage transmission lines take off, of which 4 to Lima. At the moment, there are only three of them built. Two 250-kVA station transformers, a Diesel-electric stand-by set and a storage battery cover the requirements of the station itself. Fig. 3 shows the layout of the power station composed of an engine room with built-on switchgear house. The arrangement of the equipment will be explained in describing the various parts of the plant.

II. GENERATORS.

As is seen in Fig. 4, there are three horizontal-shaft hydro-electric sets in the engine room. The generators are direct coupled to Pelton wheels each of 17,150 H.P. and are built for the following conditions:

Terminal output at an altitude of 1400 m	17,500 kVA
Active load at p.f. = 0·7	12,250 kW
Terminal voltage	6 to 6·5 kV
Frequency	60 cycles
Rated speed	514 r.p.m.
Flywheel effect	82 tm².

A century of hum

A trio of BBC transformers are the same age as *ABB Review*

SALLY DURRANT – They started service before the invention of the toaster, the TV and the Internet. Qantas and Canberra weren't even born yet. And two world wars, the Beatles, Britney Spears, Monty Python, spaceflight, penicillin and Velcro also impacted our world for better or worse over those years.

So what has withstood the test of time?

Three ABB power transformers have been stalwarts in the rural Victorian landscape of Australia for the last 100 years, actively doing their business for local utility SP AusNet. The transformers were part of a zone substation supplying the local area which also included two hydrogeneration companies.

SP AusNet's Project Manager for Capital Delivery and Engineering, Neil Sequeira agreed. "These ABB transformers were way over engineered and built to last," he said. The only loving care they seemed to require was to feed their thirst for oil. Well you wouldn't deny a 100-year-old a drink every now and then!

The three grand old dames (or gents, depending on your point of view) are being retired not because they aren't pulling their weight, but because the SP AusNet substation is being rebuilt. One of the transformers will be shipped to ABB's Moorebank, Sydney facility where it will live out its twilight years under the shade of a gum tree as part of a display of old and new – a testament to the great technology ABB continues to invent and reinvent.

Happy 100th birthday transformer 1, 2 and 3. May you enjoy your well-deserved retirement!

Sally Durrant
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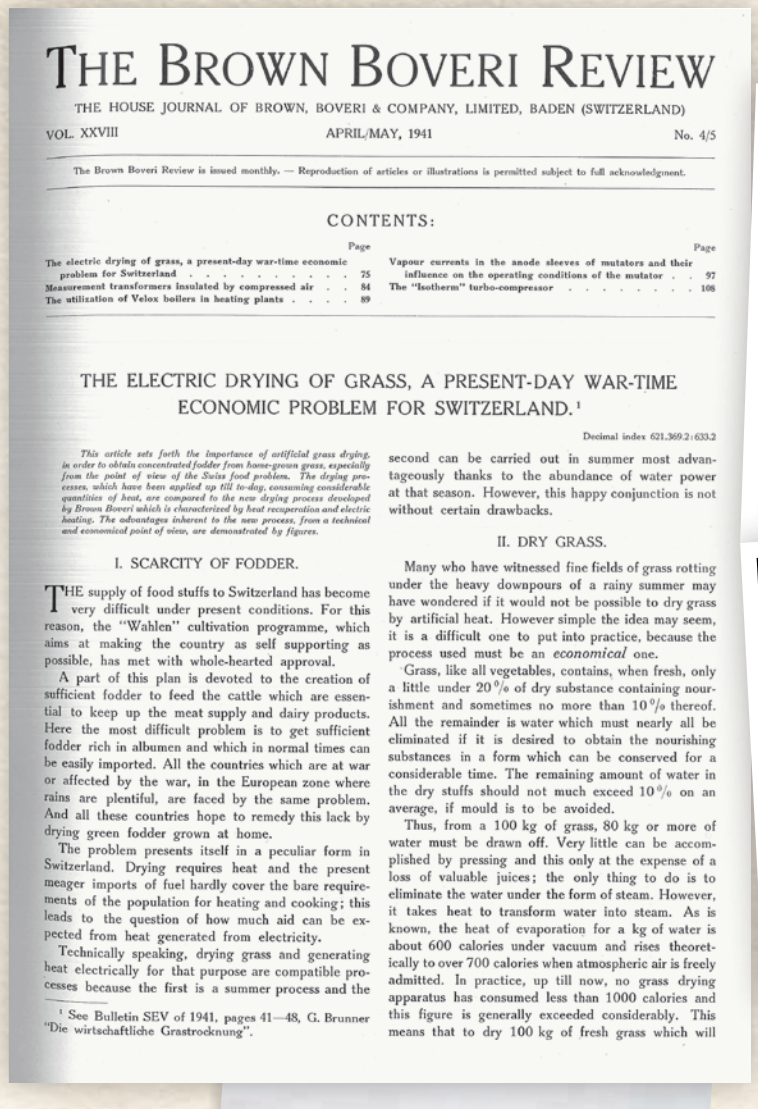
The three 9 MVA 22/66 kV GSU transformers are just as old as *ABB Review*. They were supplied by BBC in 1914.



THE BROWN BOVERI REVIEW

THE HOUSE JOURNAL OF BROWN, BOVERI & COMPANY, LIMITED, BADEN (SWITZERLAND)

VOL. XXVIII APRIL/MAY, 1941 No. 4/5

The Brown Boveri Review is issued monthly. — Reproduction of articles or illustrations is permitted subject to full acknowledgment.

CONTENTS:

THE ELECTRIC DRYING OF GRASS, A PRESENT-DAY WAR-TIME ECONOMIC PROBLEM FOR SWITZERLAND.[1]

Decimal index 621.369.2:633.2

This article sets forth the importance of artificial grass drying, in order to obtain concentrated fodder from home-grown grass, especially from the point of view of the Swiss food problem. The drying processes, which have been applied up till to-day, consuming considerable quantities of heat, are compared to the new drying process developed by Brown Boveri which is characterized by heat recuperation and electric heating. The advantages inherent to the new process, from a technical and economical point of view, are demonstrated by figures.

I. SCARCITY OF FODDER.

THE supply of food stuffs to Switzerland has become very difficult under present conditions. For this reason, the "Wahlen" cultivation programme, which aims at making the country as self supporting as possible, has met with whole-hearted approval.

A part of this plan is devoted to the creation of sufficient fodder to feed the cattle which are essential to keep up the meat supply and dairy products. Here the most difficult problem is to get sufficient fodder rich in albumen and which in normal times can be easily imported. All the countries which are at war or affected by the war, in the European zone where rains are plentiful, are faced by the same problem. And all these countries hope to remedy this lack by drying green fodder grown at home.

The problem presents itself in a peculiar form in Switzerland. Drying requires heat and the present meager imports of fuel hardly cover the bare requirements of the population for heating and cooking; this leads to the question of how much aid can be expected from heat generated from electricity.

Technically speaking, drying grass and generating heat electrically for that purpose are compatible processes because the first is a summer process and the second can be carried out in summer most advantageously thanks to the abundance of water power at that season. However, this happy conjunction is not without certain drawbacks.

[1] See Bulletin SEV of 1941, pages 41—48, G. Brunner "Die wirtschaftliche Grastrocknung".

II. DRY GRASS.

Many who have witnessed fine fields of grass rotting under the heavy downpours of a rainy summer may have wondered if it would not be possible to dry grass by artificial heat. However simple the idea may seem, it is a difficult one to put into practice, because the process used must be an *economical* one.

Grass, like all vegetables, contains, when fresh, only a little under 20 % of dry substance containing nourishment and sometimes no more than 10 % thereof. All the remainder is water which must nearly all be eliminated if it is desired to obtain the nourishing substances in a form which can be conserved for a considerable time. The remaining amount of water in the dry stuffs should not much exceed 10 % on an average, if mould is to be avoided.

Thus, from a 100 kg of grass, 80 kg or more of water must be drawn off. Very little can be accomplished by pressing and this only at the expense of a loss of valuable juices; the only thing to do is to eliminate the water under the form of steam. However, it takes heat to transform water into steam. As is known, the heat of evaporation for a kg of water is about 600 calories under vacuum and rises theoretically to over 700 calories when atmospheric air is freely admitted. In practice, up till now, no grass drying apparatus has consumed less than 1000 calories and this figure is generally exceeded considerably. This means that to dry 100 kg of fresh grass which will

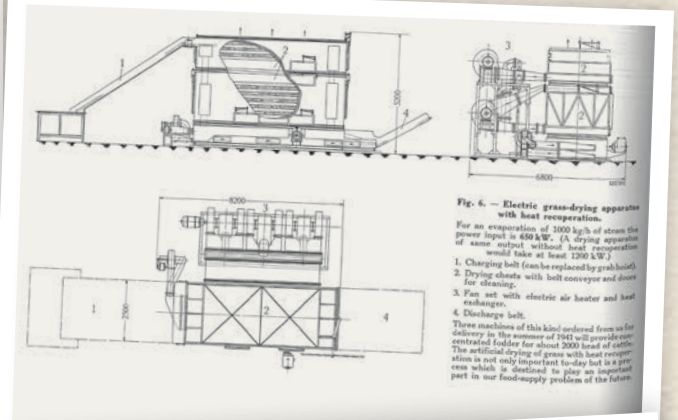


Fig. 6. — Electric grass-drying apparatus with heat recuperation.

For an evaporation of 1000 kg/h of steam the power input is 650 kW. (A drying apparatus of same output without heat recuperation would take at least 1200 kW.)

1. Charging belt (can be replaced by grab hoist).
2. Drying chests with belt conveyor and doors for cleaning.
3. Fan set with electric air heater and heat exchanger.
4. Discharge belt.

Three machines of this kind ordered from us for delivery in the summer of 1941 will provide concentrated fodder for about 2000 head of cattle. The artificial drying of grass with heat recuperation is not only important to-day but is a process which is destined to play an important part in our food-supply problem of the future.

Drying grass to make winter fodder for cattle? And that using electricity? ABB Review has no shortage of articles on unusual applications.

The Brown Boveri Review Review, April/May 1941

1942

1937

Nylon, invented by Wallace Carothers, is patented

1938

Chester Carlson invents a dry printing process called electrophotography, commonly called a Xerox

1939

BBC demonstrates the first transmission of HVDC (Wettingen to Zürich)

BBC builds the first combustion gas turbine for generating electricity

1942

Gagnan and Cousteau devise the scuba aqualung

1943

BBC builds the first 110 kV high-speed air-blast circuit breaker

The wristwatch connection

BBC's contribution to the LCD

ANDREAS MOGLESTUE – ABB and its forerunner companies have never been shy to break new ground and pioneer new technologies. Some of these escapades have taken the company well outside its usual market segment. At times, BBC was in the market for such devices as domestic ovens, fridges and floor-polishing machines. It was also once at the heart of a fashionable wristwatch.

Prototype of a patented passive-matrix super-twisted nematic LCD with 540 × 270 pixels

Today, the concept of a digital watch is mostly associated with the 1980s era. It is easily overlooked that the concept of the liquid crystal display (LCD) is much older. The Austrian botanist, Friedrich Reinitzer, is generally credited with having first observed (in 1888) a material displaying a curious intermediate state between solid and liquid. He shared his observation with the German physicist, Otto Lehmann, who investigated it further. Lehmann noticed that the substance (cholesteryl benzoate) had the refractive qualities of a crystal during its intermediate phase. He hence dubbed it a "liquid crystal."

In 1962, Richard Williams of the Radio Corporation of America (RCA) showed that the alignment of liquid crystals of p-azoxyanisole could be influenced by electric fields. His RCA colleague, George Heilmeier, made this realignment visible through the use of dyes, paving the way for LCDs. In circa 1968, Sharp commenced research in the area, recognizing the technology's potential for calculator displays. The first such calculator was launched in 1973.

In 1969, BBC began a joint research effort with Hoffmann La Roche. Initially this was based in BBC's research center in Dättwil (Switzerland), which had been inaugurated two years previously. The research effort soon bore first fruits, with Wolfgang Helfrich and Martin Schadt patenting the twisted nematic field effect in the following year. Cells using this effect displayed a greater sharpness and lower power consumption than previous LCDs. Hoffmann La Roche withdrew from the collaboration in 1972, but BBC continued developing the technology. A first production line was set up in BBC's tube factory at Birrfeld (Switzerland) in 1973. The following year, an entirely new factory was opened in Lenzburg (Switzerland). It was expanded to 4,370 m^2 in 1978.

The compact size and low power consumption of the displays made them ideal for wristwatches. In the early years, BBC collaborated with several small-volume Swiss watchmakers, but the real breakthrough came when CASIO was brought onboard. The innovative Casiotron wristwatch that was launched in 1974 used a BBC LCD. The Casiotron was not only the first LCD watch to be produced in large numbers, but also the first with a built-in calendar (even taking into account leap years).

In later years, BBC added the backlighting concept that is still used for LCDs today. In 1983, the company invented the super-twisted nematic LCD, representing another great leap forward in terms of the crispness of the display and resolution. This technology was used in the Nintendo Game Boy and early mobile phones. BBC benefitted from this mostly through patent income as the company's own production was already being ramped down. The facility in Lenzburg is today a center of power semiconductor manufacturing.

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Further reading

H. Kawamoto, "The History of Liquid-Crystal Displays," Proceedings of the IEEE, vol. 90, no. 4, pp. 460–500, Apr. 2002.
P. J. Wild, *First-Hand: Liquid Crystal Display Evolution – Swiss Contributions*, http://www.ieeeghn.org/wiki/index.php/First-Hand:Liquid_Crystal_Display_Evolution_-_Swiss_Contributions

Fig. 146. — Passenger motor car converted to electric drive "Fiat 500 Topolino". Output 4·2 H.P., lead battery 90 Ah (for ten-hour discharge), 84 V, showing how the battery is built in.
For short trips in towns with moderate inclines.
Maximum speed attained on the flat 60 km/h.

What we today call electromobility is no new field for ABB.

The Brown Boveri Review, January/February/March 1942

Moving transformers in 1908 (above) and 1937 (left)

The Brown Boveri Review, November/December 1942

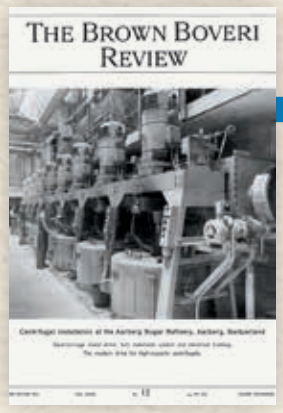
1944

1944

BBC develops the first high-speed locomotive with a direct drive system

1945

George Orwell publishes *Animal Farm*



1946

1946

Disposable diapers are invented by Marion Donovan

1947

The transistor is invented by Bardeen, Brattain, and Shockley

1951

1951

First *BBC Review* cover in color

COMPARATIVE STUDY OF SOME PROBLEMS OF A.C. AND D.C. POWER TRANSMISSION. THE D.C. TRANSMISSION READY FOR PRACTICAL APPLICATION.

Decimal Index 621.315.051.024
621.315.051.025

The article compares the economic and some technical aspects of the two methods of transporting electric power. Both A.C. and D.C. transmission have progressed considerably in recent years and it is necessary therefore to revise earlier conclusions as to their relative merits.

It appears that the D.C. transmission is sufficiently out of the purely experimental stage that an industrial installation of a certain importance would be entirely justified.

THE realization of the decreasing world reserves of coal and other fuels has led to a renewed interest in the possibilities of utilizing all existing sources of hydro-power. Since most of the sites situated near to the consumers are already exploited, it will be necessary in a not too distant future to build hydrostations that are increasingly remote from the ultimate load centres. The question of how to transport over very long distances the power produced is becoming more and more important therefore. It is generally admitted that D.C. is more advantageous economically if the transmission distance exceeds a few hundreds of kilometres, but it remains to be shown beyond which point the standard A.C. system loses its superiority. Should this transition occur at relatively short distances D.C. would immediately become applicable not only for super-transmissions, but also for large interconnections between to-day neighbouring networks. It is obvious, however, that economic considerations are not conclusive until it has been definitely established that the converting equipment required at sending and receiving stations is sufficiently reliable for the capacities involved. It is one of the purposes of this article to show that this point has been reached to-day.

(a) *Comparison on the Basis of Cost.*

On the occasion of the 50th anniversary of Brown Boveri in 1941, we made a comparison of A.C. versus D.C. transmission on an economic basis[1]. The result of our studies seemed to indicate that for distances in excess of 200 to 300 km D.C. is more economical. Since then our research in both directions has continued. A thorough investigation of A.C. transmission stability has shown that intermediate synchronous condenser stations are not absolutely necessary as was commonly believed before. By using special induction type (asynchronous) generators, or by applying novel methods of field control to otherwise normal synchronous alternators, it appears possible to-day to bridge much longer distances than was thought practical a short time ago[2]. This discovery necessitates a revision of our previous comparative calculations.

The main reason why D.C. is at an advantage over very long distances is the fact that a D.C. transmission line is much less costly than an equivalent three-phase circuit. This is demonstrated in Fig. 1, which gives the first cost of the two kinds of lines for variable amounts of power to be transmitted. The comparison is made for double lines on single towers, i. e. for six wires in the case of A.C. and four and two wires respectively for D.C., in addition to the ground wire. Both lines are laid out for one per cent loss per 100 km. The price figures shown are based on average pre-war (1939) costs of construction and include copper conductors, galvanized steel ground wire, earthing of the towers, insulator strings, fittings, hot process galvanized towers, foundations, erection, right of way, prospecting and planning, and incidental expenses[3]. A comparison of curves 1 and 2 shows that the double D.C. line is over 30 % less expensive than the equivalent A.C. line. A defective cable puts one half of the A.C. circuits out of commission, but only one quarter of the D.C. circuits, as it is still possible to operate the remaining conductor of the defective line on full current and half the voltage by utilizing

[1] Brown Boveri Rev., October 1941, page 249.

[2] This question will be fully dealt with in a later issue of this review.

[3] Cost figures by courtesy of Motor Columbus A. G.

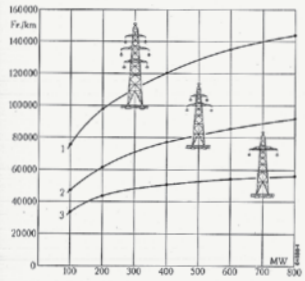


Fig. 1. — First costs of three-phase and D.C. lines for different design loads, based on pre-war prices (1939).

1. Double-circuit three-phase transmission for operating voltages of 150 to 400 kV.
2. Double-circuit D.C. transmission for operating voltages of 300 to 600 kV.
3. Single circuit D.C. transmission for operating voltages of 300 to 800 kV.

The cost figures given are for lines of equal loss (1% per 100 km).

The first cost of D.C. lines is so much lower than that of three-phase lines that D.C. is at an undeniable advantage over long distances. If temporary ground return of D.C. is admitted during disturbances, a three-phase line as per curve 1 is equivalent to a D.C. line according to curve 3, which shows what advantages are to be expected from this possibility.

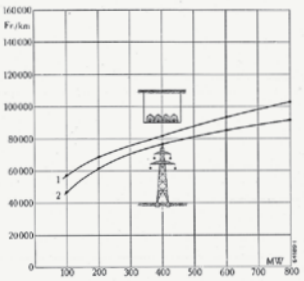


Fig. 2. — First costs of overhead and cable lines for D.C., for different design loads, based on pre-war prices (1939).

1. Cable line for 400 to 700 kV.
2. Overhead line 300 to 600 kV (identical with curve 2, Fig. 1)

The cost figures given are for lines of equal loss (1% per 100 km)

First costs of overhead lines and cables differ little from each other. With D.C. transmission it should be economically feasible to build long distance cable transmissions.

the earth as return path. If full advantage is taken of this possibility one is led to compare an A.C. line as per curve 1 with a D.C. line as per curve 3. In both cases a defective cable reduces to one half the power that can be carried by the remaining circuit. The inherent reliability of the D.C. line should be rather higher since there is less likelihood of a defect with two wires than with six. On the other hand it must be admitted that the conversion from A.C. to D.C. and vice versa introduces additional equipment which may itself be the source of trouble. This risk can be reduced to any desired degree by providing spare converters. The difference between curves 2 and 3 represents the possible savings if emergency operation with earth return is considered unobjectionable. In this case the D.C. line costs less than one half of the six conductor A.C. line as per curve 1.

The assumption that temporary ground return is permissible must not be made for D.C. transmission, but in a similar way for A.C. transmission as well. As a matter of fact, we are quite convinced that extra high voltage A.C. transmission will rely on solidly grounded neutral operation[1]. In both cases unsymmetrical communication circuits are, of course, subject to interference during certain kinds of faults, so that this problem must be tackled at any rate. We are confident it can and will be solved regardless of the method of power transmission eventually selected.

As mentioned above a D.C. line is much less expensive to build than an equivalent three-phase line. This is due to the combined effect of a number of causes, the most important of which are the following: —

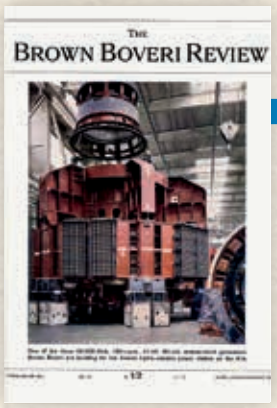
1. The smaller number of conductors entails fewer insulators and simplifies the tower design.
2. A given line can be operated at a higher voltage with D.C. than with A.C. The voltage to earth can be increased in the ratio of $\sqrt{2}:1$, the voltage between conductors (as determined by corona), theoretically, in the ratio $\frac{2\times\sqrt{2}}{\sqrt{3}} = 1{\cdot}63$.
3. Since there is no skin effect with D.C., hollow conductors are not necessary except for extremely high

[1] Th. Boveri: Bull. Schweiz. Elektrotechn. Ver. 1944, p. 270.
Brown Boveri Rev., October 1941, pp. 281 and 303.

The arguments for using DC transmission to integrate renewable generation are far from new, as this 1945 contribution shows.

Despite BBC's early activities, it was the ASEA side of the company that established early leadership in the field of HVDC (see also page 33 of this edition of *ABB Review*).

The Brown Boveri Review, September 1945



1954

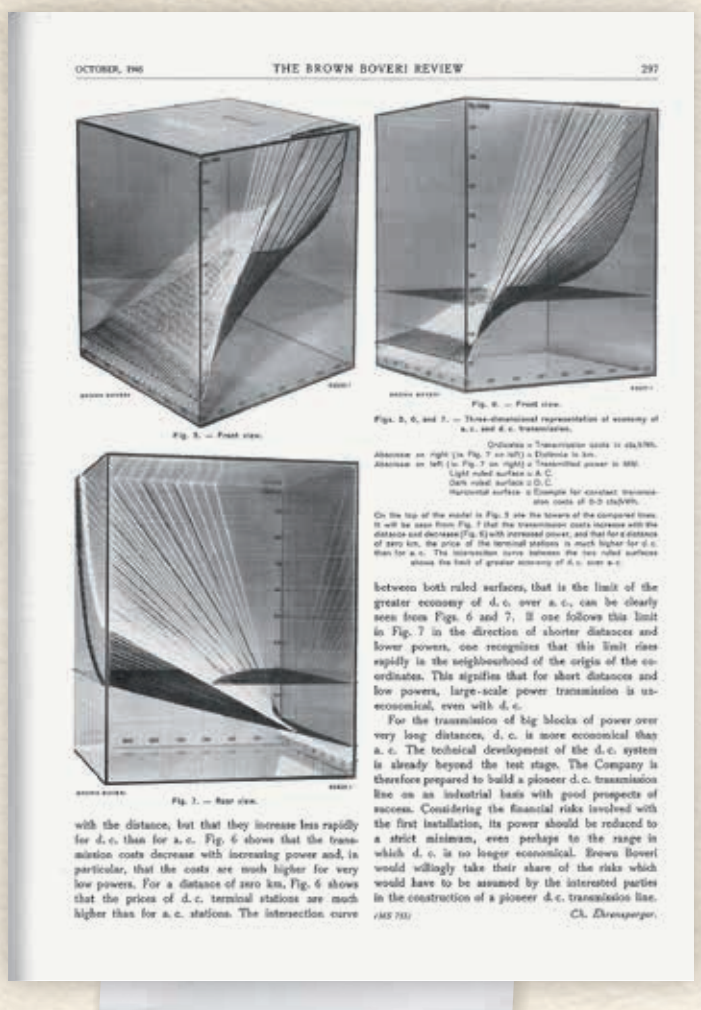
1952
Jonas Salk develops a vaccine against poliomyelitis (polio)

1953
ASEA is the first company in the world to manufacture synthetic diamonds

1954
ASEA lays the first-ever commercial HVDC transmission line

1960
Theodore Maiman invents the laser

1961
Bob Dylan makes his debut performance in Greenwich Village, New York



OCTOBER, 1946 THE BROWN BOVERI REVIEW 297

Fig. 5. — Front view.

Fig. 6. — Front view.

Figs. 5, 6, and 7. — Three-dimensional representation of economy of a. c. and d. c. transmission.

Ordinates = Transmission costs in cts/kWh.
Abscissæ on right (in Fig. 7 on left) = Distance in km.
Abscissæ on left (in Fig. 7 on right) = Transmitted power in MW.
Light ruled surface = A. C.
Dark ruled surface = D. C.
Horizontal surface = Example for constant transmission costs of 0·3 cts/kWh.

On the top of the model in Fig. 5 are the towers of the compared lines. It will be seen from Fig. 7 that the transmission costs increase with the distance and decrease (Fig. 6) with increased power, and that for a distance of zero km, the price of the terminal stations is much higher for d. c. than for a. c. The intersection curve between the two ruled surfaces shows the limit of greater economy of d. c. over a. c.

Fig. 7. — Rear view.

with the distance, but that they increase less rapidly for d. c. than for a. c. Fig. 6 shows that the transmission costs decrease with increasing power and, in particular, that the costs are much higher for very low powers. For a distance of zero km, Fig. 6 shows that the prices of d. c. terminal stations are much higher than for a. c. stations. The intersection curve between both ruled surfaces, that is the limit of the greater economy of d. c. over a. c., can be clearly seen from Figs. 6 and 7. If one follows this limit in Fig. 7 in the direction of shorter distances and lower powers, one recognizes that this limit rises rapidly in the neighbourhood of the origin of the coordinates. This signifies that for short distances and low powers, large-scale power transmission is uneconomical, even with d. c.

For the transmission of big blocks of power over very long distances, d. c. is more economical than a. c. The technical development of the d. c. system is already beyond the test stage. The Company is therefore prepared to build a pioneer d. c. transmission line on an industrial basis with good prospects of success. Considering the financial risks involved with the first installation, its power should be reduced to a strict minimum, even perhaps to the range in which d. c. is no longer economical. Brown Boveri would willingly take their share of the risks which would have to be assumed by the interested parties in the construction of a pioneer d. c. transmission line.

(MS 751) Ch. Ehrensperger.

Long before MATLAB™ was invented, *ABB Review* was already using 3-D depictions to present results.

The Brown Boveri Review, October 1946

There's nothing new about using refuse as a fuel.

Brown Boveri Review, July 1969

Steam and Power from Refuse

628.492:621.182
628.492:621.311

The question of refuse incineration combined with steam and power generation is discussed.

This method of refuse disposal, its requirements and consequences, are still not widely known.

It is known that, beyond a certain annual volume of refuse, the running costs (including capital charges) of an incineration plant can be lowered appreciably by using the heat to produce steam and electricity, which is then sold. When the electricity undertakings negotiate tariffs for purchasing electricity from power-generating incineration plant, however, the agreed rates should be such that sales of electricity lower the specific cost of incineration per ton of refuse. Purchase prices between SFr. 0·03 and 0·05/kWh are generally sufficient.

An example of a project, based on practical data, illustrates the advantages of this method of incineration.[1]

Introduction

As industrialization and population density increase, so too do the problems and necessity of efficient refuse disposal. The specific quantity of refuse per head of population rises every year by several per cent, though there are certain differences between rural, urban and industrial areas. It requires a specialist to appreciate the problem in all its aspects and, despite its complexity, to find a simple but economical solution.

Refuse Incineration

It has been clearly demonstrated that the most hygienic way to dispose of refuse is to burn it, whereupon the combustion process gives rise to slag and flue gases. Because of the high temperatures in the boiler furnace, the slag can be considered as sterile, with no risk of decomposing. It can be safely dumped or used for some other purpose.

Refuse burns at temperatures between 900 and 1000 °C. Odourless flue gases can be guaranteed only if the combustion gases pass through a zone of temperatures high enough to eliminate smells, i.e. about 800 °C. The hot gases must also be cooled and cleaned before they are discharged from the chimney into the atmosphere. To be filtered, they must first be cooled to about 300 °C. This is usually done by injecting water or adding cold air. The heat remaining in the flue gases is thus removed without being utilized.

It is here that economic considerations enter into the picture. The heat in the flue gases is energy, and this energy can be used to generate steam and electricity.

Steam and Power Generation

The calorific value of refuse increases year by year. The annual mean value for urban conditions, for example, has now passed 2200 kcal/kg. This refuse thus has almost the same calorific value as young brown coal which, despite its low heat content, is used in some countries for generating electricity.

Assuming this calorific value of 2200 kcal/kg and a boiler efficiency of 65 %, one ton of refuse produces roughly 2·3 tons of steam. Generated in a well designed boiler, this quantity of steam can be passed through a condensing turboset and produce up to 500 kWh.

[1] A film produced by the Swiss Association for the Protection of Water and Air against Pollution entitled "Waste—the Penalty of Affluence" and presented to the 4th International Congress of the International Research Group on Refuse Disposal (IRGR) on 2nd June 1969 in Basle came to the same conclusion as described in this article.

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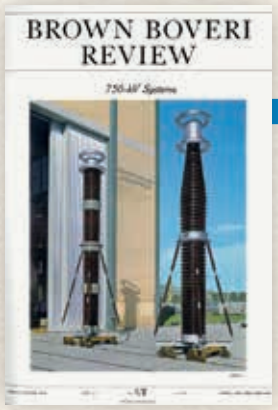


1964

1962

Rachel Carson publishes *Silent Spring*, frequently cited as being one of the key catalysts that inspired the environmental movement

The audio cassette is invented

1964

BASIC is invented by John George Kemeny and Tom Kurtz

1965

Compact disc is invented by James Russell

1967

First calculator is invented

1968

Douglas Engelbart demonstrates the world's first computer mouse

Fig. 116. — Brown Boveri radiotelephony equipment for Paris City Police
This equipment permits excellent telephone communication between patrol cars and police headquarters within a 50 km radius.

Radio equipment for the Parisian police.

The Brown Boveri Review,
January/February 1949

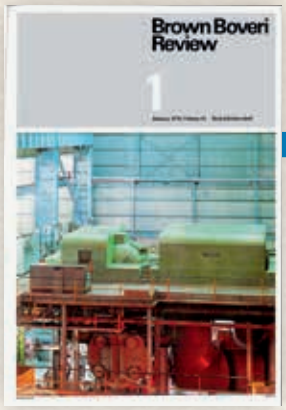
Installing power equipment in northern Canada sometimes called for unconventional methods.

The Brown Boveri Review,
July/August 1955

JULY/AUGUST 1955 THE BROWN BOVERI REVIEW 245

Fig. 05. — The rough and ready transport facilities in Northern Canada necessitated the PLC equipment being taken by air to Snare River power station near the Great Slave Lake

Fig. 06. — Snare River power plant supplies the goldmining town of Yellow Knife over a 115-kV line 150 km long. This line also serves the carrier-frequency telephone link, which is the only means of communicating with the outside world.



1974

1975

1969

BBC develops the first gearless cement drive

1971

Women achieve equal voting rights in Switzerland

1974

Erno Rubik gives the world the Rubik's cube

ASEA launches one of the world's first electrical industrial robots

1975

Digital camera invented by Steve Sasson of Kodak

1976

Inkjet printer is invented

THE BROWN BOVERI REVIEW

ISSUED BY BROWN, BOVERI & COMPANY, LIMITED, BADEN (SWITZERLAND)

VOL. 42 SEPTEMBER 1955 No. 9

CONTENTS:

THE FIRST 150-MW TURBO-GENERATOR SET IN EUROPE

621.165:621.313.323 (43)

The largest turbo-generator set in Europe, having an output of 150 MW, was supplied by Brown Boveri to the lignite-fired power station of Weisweiler, near Aachen, Germany, where it has been in operation for several months. In the following article the authors describe in detail the turbine, the alternator and the exciter.

At the beginning of 1955 in the Weisweiler power station near Aachen, belonging to the Rheinisch-Westfälisches Elektrizitätswerk AG. (RWE), Europe's first 150-MW turbo-generator set was taken into service. Since then the plant has operated without disturbance, delivering its full output to the supply system.

The Weisweiler Power Station

The newly-built 350-MW steam-driven power station,[1] which was planned by the RWE, employs as fuel low-grade lignite having a high ash and moisture content. In power stations such as this, burning so little high-grade coal, capital is burdened to a considerable degree with the cost of producing current: operational expenditure is high. When planning the Weisweiler power station greatest stress was placed on: low building costs, short building time (i.e. reduced interest on building capital), maximum reliability (i.e. high utilization factor), and low operating costs.

[1] W. Kretschmer: Neuzeitliche Braunkohle-Grosskraftwerke Braunkohle, Wärme und Energie 1953, No. 19/20, p. 399–416.

W. Kretschmer: Das Braunkohle-Kraftwerk Weisweiler. Elektrizitätswirtschaft 1955, Vol. 54, No. 11, p. 342–50.

The ever-increasing demand for power made on the supply system of the RWE (about 8% per annum) and the desire to produce with a minimum of delay as much additional electrical energy as possible for the outlay of capital led inevitably to the employment of large units, as the specific cost of plant reckons in relation to the increase in unit size. The power station (see title page of this issue) is planned for an immediate output of 350 MW, but full consideration has been taken of the need for future expansion. In view of the fact that the output of large turbo-sets is always interrelated with the power being supplied to the system and bearing in mind that the power available to the entire German grid amounts to approximately 6000 MW, it will be recognised that the choice of one 150-MW and two 100-MW turbo-sets—corresponding to 2·5% (or 1·77%) of the total power in the grid—was in line with the obvious trend to employ large units.

The thermal circuits of the individual units are quite independent of each other and interconnections are eliminated; and on the current-producing side, also, the unit system is employed for the three sets; in fact, each system is fully independent as far as the h.v. transmission lines, beyond the transformers. In order to achieve optimum reserve and low partial-load conditions each of the two 100-MW turbines are supplied with steam by two 200-t/h high-pressure, drum-type boilers, and the 150-MW turbine, by two 300-t/h forced-circulation boilers.

THE MAGNETOSTRICTIVE RESONATOR AND ITS USE IN OSCILLATORS AND FILTERS

538.652
621.373.1:538.652
621.372.54:538.652

Magnetostrictive resonators are electro-mechanical oscillatory systems, in which the electrical and mechanical quantities are related according to magnetostrictive laws. In this article, the author examines practical and theoretical aspects of such elements and describes their construction and application.

As with all electro-mechanical principles, attempts were also made to apply the magnetostrictive effect in resonant oscillatory systems and electro-mechanical transducers. The first investigations into magnetostrictive resonators as frequency-determining elements in tube oscillators provided most encouraging results.[1] Consequent on the high mechanical quality of such resonators, it was possible to attain a degree of stability quite equal to that obtainable from quartz crystals. But the temperature coefficient of the frequency for the particular alloy used was much too large ($a_f = 10^{-4}/°C$) to permit replacement of quartz by magnetostriction oscillators. The frequency range was practically limited to 10–50 kc/s. At lower frequencies the range was restricted by the length of the rod, at higher frequencies pure electrical resonances blanketed the magnetostrictive effect.

By systematic investigation it has become possible to develop magnetostrictive elements for the frequency range 20–350 kc/s, in which all earlier shortcomings have been made good. By employing a suitable alloy, subjected to special thermal treatment, for the vibrating rod the temperature coefficient of frequency was reduced to $a_f \approx 5{,}10^{-7}/°C$. Moreover, the layout of the vibrator and the selection of the magnetic working point made it possible to avoid pure electrical resonances and to ensure that the magnetostrictive effect was large enough throughout the entire frequency range to determine the frequency definitively in oscillator circuits. As a result of the qualities attained—high degree of stability and small temperature coefficient—it is now possible to use magnetostriction vibrators for the same purposes as quartz crystals without needing a thermostat, due to the low temperature coefficient. For instance, all Brown Boveri single-sideband PLC (power line carrier) sets are equipped with magnetostriction oscillators without thermostats.

[1] G. W. Pierce: Magnetostriction Oscillators. Proc. Inst. Radio Engrs, 1929, Vol. 17, No. 1, p. 42–68.

Theory of Magnetostrictive Resonators

Due to the interaction of the magnetostrictive effect and the mechanical behaviour of a (longitudinally) vibrating rod, the electrical quantities in the coil surrounding the rod are related to the mechanical quantities. Depending on whether the rod is surrounded by one or two magnetically decoupled coils, it is usual to refer to a two- or four-terminal network. The latter is also known as a magnetostriction element.

Before we commence to deduce the characteristic equations, let us first explain what is meant by magnetostrictive effects.

1. If a sample of ferromagnetic material is exposed to a magnetic field, its geometrical dimensions change.

2. If a sample of ferromagnetic material is in a magnetic field and mechanical strains are set up in it by external forces, its state of magnetization changes.

A quantitive formulation of the magnetostrictive phenomena is, for present purposes, expressed by Joule's and Villari's laws:

Joule's law: If a rod of ferromagnetic material is magnetized axially, the change in axial length is proportional to the change in field strength and to the length of the rod.

$$dl = \lambda l_0 \, dH \quad (\sigma \text{ constant}) \tag{1}$$

Villari's law: If a rod of ferromagnetic material, pre-magnetized axially, is subjected to an axial mechanical strain, the magnetic induction varies in proportion to this strain.

$$dB = \lambda \, d\sigma \quad (H \text{ constant}) \tag{2}$$

Observe that the magnetostriction is independent of the direction of the field:

$$\Delta l = F(H) = F(-H) \tag{3}$$

If, in the event of a sinusoidal field, it is desired that the change of length shall also be sinusoidal, pre-magnetization is essential. The proportionality factor λ for both equations (1) and (2) is called the magnetostriction constant, although λ is dependent on the pre-magnetization H_0. Depending on the material, λ can be positive or negative.

Deduction of the Equation for a Magnetostrictive Four-Terminal Network

For an element of rod of constant cross-section and length dx, the following equations of motion are valid in the x-axis (ignoring internal friction):

$$d^2\xi = -s \, d\sigma \, dx \quad (H \text{ constant}) \tag{4}$$

$$d\sigma = -\rho \frac{d^2\xi}{dt^2} \cdot dx \tag{5}$$

where $d\xi$ = change of length of element dx
s = stiffness = $1/E$ (E = Young's modulus)
σ = mechanical strain
ρ = specific gravity.

Further, for ferromagnetic material, the appropriate version of the magnetostrictive equation (1) must be added

$$d^2\xi = \lambda \, dh \, dx \quad (\sigma \text{ constant}) \tag{6}$$

The latter is true, provided the rod is premagnetized by a d.c. field and the alternating field $h \ll H_0$. By combining (4) and (6) and substituting v for $d\xi/dt$, we obtain the following equation for simultaneous variation of mechanical strain and field strength:

$$\frac{dv}{dx} = -s \frac{d\sigma}{dt} + \lambda \frac{dh}{dt} \tag{7}$$

and from (5), substituting dv/dt for $d^2\xi/dt^2$:

$$\frac{d\sigma}{dx} = -\rho \frac{dv}{dt} \tag{8}$$

Referring to the magnetostrictive law (2), we find the equation of the magnetic circuit consisting of the magnetostrictive rod, surrounded by a coil of N turns and the magnetic return circuit, as follows:

$$\vartheta = 4\pi i N = \frac{\lambda}{\mu_0 \mu} \int \sigma \cdot dx = \phi \sum_\nu \frac{l_\nu}{\mu_\nu q_\nu} = \phi R_{m\,tot} \tag{9}$$

from which, introducing

$$u = N \frac{d\phi}{dt} = \frac{4\pi N}{R_{m\,tot}} \left[N \frac{di}{dt} - \frac{\lambda}{\mu_0 \mu} \int_0^l \frac{d\sigma}{dt} \, dx \right] \tag{10}$$

we obtain, for the internal field strength of the element of rod dx:

$$\frac{dh}{dt} = u \frac{R_m}{Nl} + \frac{\lambda}{\mu_0 \mu} \cdot \frac{d\sigma}{dt} \tag{11}$$

where l = length of the rod
R_m = reluctance of the rod.

Thus, by substituting in (7), we obtain the relation between the electrical and mechanical quantities

$$\frac{dv}{dx} = -s' \frac{d\sigma}{dt} + \lambda \frac{R_m}{Nl} u \tag{12}$$

where $s' = s\,(1 - 4\pi\lambda^2/\mu s)$. For a sinusoidal impressed voltage $u = Ue^{j\omega t}$, the simultaneous equations (8) and (12) give the following solution:

$$\sigma = \sigma_0 \cos\gamma x - j z v_0 \sin\gamma x - j z k u (1 - \cos\gamma x) \tag{13}$$

$$v = \frac{\sigma_0}{jz} \sin\gamma x + v_0 \cos\gamma x + k u \sin\gamma x \tag{14}$$

where $z = \sqrt{\frac{\rho}{s'}}$ $\qquad \gamma = \omega\sqrt{\rho s'}$ $\qquad k = \frac{\lambda R_m}{N l}$

σ_0, v_0 = are mechanical strain and velocity at the end of the rod $x = 0$. If we substitute (10) in the equations (13) and (14) with the boundary condition $\sigma_0 = 0$ (i.e. the rod has a free end), we obtain the electromechanical transducer equations:

$$u = \frac{N\gamma l}{jz\lambda R_m} \left[\sigma_l \frac{\cos\gamma l}{1 - \cos\gamma l} + jz v_l \frac{\sin\gamma l}{1 - \cos\gamma l} \right] \tag{15}$$

$$i = u \frac{R_{m\,tot}}{j\omega 4\pi N^2} + \frac{\lambda z}{j\gamma N\mu} \cdot \left[\frac{\sigma_l}{jz} \frac{\gamma l \cos\gamma l - \sin\gamma l}{1 - \cos\gamma l} + v_l \frac{\gamma l \sin\gamma l - 2(1 - \cos\gamma l)}{1 - \cos\gamma l} \right] \tag{16}$$

Control room of a hydroelectric power plant in Italy. ABB still equips control rooms today – although today's equivalent looks very different.

The Brown Boveri Review, January 1955

Fig. 49a. — Control room in the underground power station of Santa Massenza belonging to the Società Idroelettrica Serca-Molveno, Italy
Right: the central control desk for generators, transformers and transmission lines; in the centre: the mimic diagram; and adjoining, the switch panels for measuring, recording, controlling and protection. Built by Tecnomasio Italiano Brown Boveri, Milan.

Fig. 2. — No machine could help on the last part of the way up to La Dôle television transmitter building which is at an elevation of 1600 m: muscular effort was the only way the separate sections of the visual transmitter, weighing some 3 tons altogether, could be pushed up the mountainside

Manhauling equipment on sleds for the La Dôle television transmitter, Switzerland.

The Brown Boveri Review, March 1955

1984

1987

1991

1978

First IVF baby is born

1987

First *BBC Review* in Spanish

1988

ASEA and BBC merge to create ABB

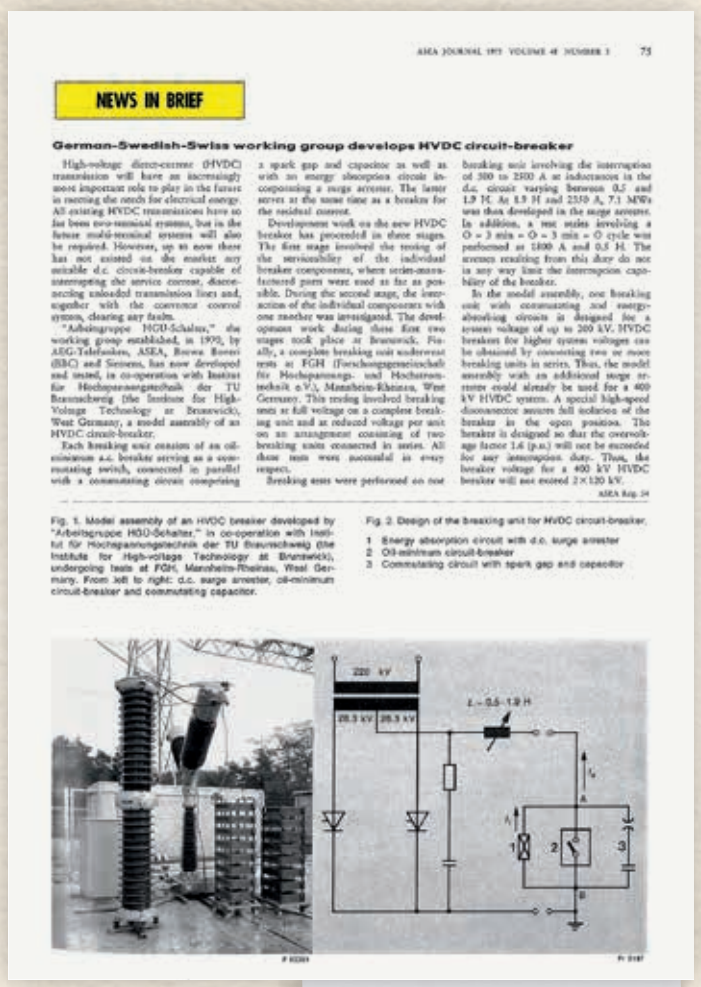
Stephen Hawking publishes *A Brief History of Time*

1990

ABB launches the Azipod® electric propulsion system for ships

1991

First *ABB Review* in Russian



NEWS IN BRIEF

German-Swedish-Swiss working group develops HVDC circuit-breaker

High-voltage direct-current (HVDC) transmission will have an increasingly more important role to play in the future in meeting the needs for electrical energy. All existing HVDC transmissions have so far been two-terminal systems, but in the future multi-terminal systems will also be required. However, up to now there has not existed on the market any suitable d.c. circuit-breaker capable of interrupting the service current, disconnecting unloaded transmission lines and, together with the convertor control system, clearing any faults.

"Arbeitsgruppe HGÜ-Schalter," the working group established, in 1970, by AEG-Telefunken, ASEA, Brown Boveri (BBC) and Siemens, has now developed and tested, in co-operation with Institut für Hochspannungstechnik der TU Braunschweig (the Institute for High-Voltage Technology at Brunswick), West Germany, a model assembly of an HVDC circuit-breaker.

Each breaking unit consists of an oil-minimum a.c. breaker serving as a commutating switch, connected in parallel with a commutating circuit comprising a spark gap and capacitor as well as with an energy absorption circuit incorporating a surge arrester. The latter serves at the same time as a breaker for the residual current.

Development work on the new HVDC breaker has proceeded in three stages. The first stage involved the testing of the serviceability of the individual breaker components, where series-manufactured parts were used as far as possible. During the second stage, the interaction of the individual components with one another was investigated. The development work during these first two stages took place at Braunschweig. Finally, a complete breaking unit underwent tests at FGH (Forschungsgemeinschaft für Hochspannungs- und Hochstromtechnik e.V.), Mannheim-Rheinau, West Germany. This testing involved breaking tests at full voltage on a complete breaking unit and at reduced voltage per unit on an arrangement consisting of two breaking units connected in series. All these tests were successful in every respect.

Breaking tests were performed on rest breaking unit involving the interruption of 300 to 2500 A at inductances in the d.c. circuit varying between 0.5 and 1.9 H. At 1.9 H and 2500 A, 7.1 MWs was thus developed in the surge arrester. In addition, a test series involving a O – 3 min – O – 3 min – O cycle was performed at 1800 A and 0.5 H. The stresses resulting from this duty do not in any way limit the interruption capability of the breaker.

In the model assembly, one breaking unit with commutating and energy-absorbing circuits is designed for a system voltage of up to 200 kV. HVDC breakers for higher system voltages can be obtained by connecting two or more breaking units in series. Thus, the model assembly with an additional stage arrester could already be used for a 400 kV HVDC system. A special high-speed disconnector assures full isolation of the breaker in the open position. The breaker is designed so that the overvoltage factor 1.6 (p.u.) will not be exceeded for any interruption duty. Thus, the breaker voltage for a 400 kV HVDC breaker will not exceed 2×120 kV.

ASEA Rep. 24

Fig. 1. Model assembly of an HVDC breaker developed by "Arbeitsgruppe HGÜ-Schalter," in co-operation with Institut für Hochspannungstechnik der TU Braunschweig (the Institute for High-voltage Technology at Brunswick), undergoing tests at FGH, Mannheim-Rheinau, West Germany. From left to right: d.c. surge arrester, oil-minimum circuit-breaker and commutating capacitor.

Fig. 2. Design of the breaking unit for HVDC circuit-breaker.
1 Energy absorption circuit with d.c. surge arrester
2 Oil-minimum circuit-breaker
3 Commutating circuit with spark gap and capacitor

In 1988, ASEA and ABB merged to form ABB. But this was far from the first cooperation between the two companies. As this article documents, The companies collaborated in a project to create an HVDC breaker during the 1970s.

ASEA Journal, vol. 48, no. 3, 1975

ABB drives can take your car for a test drive.

Brown Boveri Review, March 1986

Four-Roller Test Rig for Four-Wheel Drive Vehicles

Production of four-wheel drive vehicles is increasing year by year. To speed up development work, the vehicle industry requires suitable test rigs. Brown Boveri have responded to this need by developing and building a dynamic four-roller test rig especially for this type of vehicle. The rig has four drives rated 110 kW and can be used to test vehicles with axles spaced 2 to 3.5 m at speeds up to 240 km/h.

R. Gee works on test rig projects in our Industrial Plants Division, Mannheim, Federal Republic of Germany.

Four-wheel drive vehicles are appearing on the market in ever-increasing numbers. As a great many vehicle trials are performed today on test rigs, suitable roller performance rigs had to be developed and built for this type of vehicle. Features in favour of testing on rigs are:

- The conditions encountered during road tests can be simulated reliably on modern test rigs.
- Test cycles are far easier to reproduce on test rigs than on the open road.
- Trials carried out on test rigs are more cost-effective and less time-consuming than road tests.

A multi-purpose vehicle test rig must satisfy the following requirements:

- An individually driven roller must be provided for each wheel of the vehicle.
- Shafts connecting the rollers should be avoided to ensure access to all parts of the vehicle from below.

Two stipulations result from these requirements: the rollers must be synchronized and they must be capable of displacement. Brown Boveri consequently designed and built a test rig for the more traditional front-wheel and rear-wheel drives as well as for the four-wheel drive. This test rig is described in the following.

The rig is intended for putting vehicles, their functional assemblies and individual components through their paces under realistic road conditions.

Brown Boveri provided the following services and equipment for the test rig:

- Mechanical and electrical design of the test rig, plus delivery of the control hardware and running resistance simulator
- All calculations connected with vibrations and the layout design of the test rig foundations
- Structural design

The customer consulted Brown Boveri in all matters concerning the civil engineering. This covered items such as the facilities for supplying cooling air and water and for emission removal, all of which were provided by the customer.

Operators and suppliers of this type of test facility often refer to them as roller bed or performance test rigs.

Fig. 1 – Rear-wheel drive vehicle on the four-roller performance test rig

1994

2003

1997

Deep Blue computer defeats world chess champion Gary Kasparov

1998

World's longest (1,990 m) suspension bridge, the Akashi Kaikyo, opens in Japan

2001

First full Web presence of *ABB Review*

Apple launches the iPod

2002

ABB links the AC networks of South Australia and Victoria with the world's longest underground transmission

2003

First *ABB Review* in Chinese

Brown Boveri Systems Control One of the Most Modern Baggage Sorting Facilities in the World

Swissair entrusted Brown Boveri with the design and delivery of control systems for the new baggage sorting facility in finger dock A at Zurich airport in Switzerland. By installing the BBC-PARTNERBUS® and the INDACTIC® 15 control system, Brown Boveri contributed to the reliability and transparency of this facility, in which decentralized sorting computers are a main feature.

***M. Heuer** is in charge of special projects in the Airport Planning Department of Swissair and has overall responsibility for the new sorting facility. Kloten, Switzerland*

***K. Kimmig** is Project Manager in charge of the equipment and systems delivered by our company. Turgi, Switzerland*

Introduction

Flight passengers rightly expect the baggage they checked in before departure to arrive with them at their destination. This presumes, however, that the baggage travels on the same flight as the passengers. To ensure that this is always so, Zurich airport placed in operation, on November 1, 1985, one of the most modern baggage sorting facilities in the world.

Design Concept

The design concept used for the new sorting system in terminal A is similar to that used for the system in terminal B, which has given reliable service for more than ten years. With the new system, Zurich airport now offers passengers the following services:

- Check-in at any time on the day of travel up until shortly before the flight departure
- A free choice of the shortest queue at the check-in counters to any destination
- Flight connections with short transfer times can be used in the knowledge that the baggage will also arrive on time at the final destination

If these services to the customer are to be guaranteed, however, it must be possible to sort large quantities of baggage and direct the suitcases, etc. to their correct destinations. High-speed conveyor belts, such as those linking terminal A to terminal B, are one means by which this can be accomplished. Another is to ensure a high level of operational reliability.

Transport and Sorting of the Baggage

The check-in counters in the newly designed departure hall of terminal A are divided into two groups. Each counter is linked by a conveyor belt to the baggage sorting room, which is in the basement of the finger dock. To enable passengers to check-in shortly

Fig. 1 – Suitcases entering the sorting bay

Maybe BBC technology helped sort your airline luggage!

Brown Boveri Review,
May 1986

Fig. 91. — 1100 h.p. d.c. locomotive of the Viação Férrea Federal Leste Brasileiro em Salvador

Ten locomotives of this type were equipped by Brown Boveri with driving motors, circuit breakers and voltage converters with quick-acting regulators.

BBC supplied the motors, circuit breakers and regulators for this 3 kV DC, 1,00 hp locomotive headed for Brazil in 1955. BBC has since its early days been a supplier to the railway industry, and still is today.

The Brown Boveri Review,
January 1955

2008

2010

2013

2008

World's tallest Ferris wheel, Singapore Flyer, opens in Singapore

2009

Usain Bolt sets a new men's 100 m sprint record of 9.58 s

2010

ABB opens the world's highest substation in the world's tallest building, the *Burj Khalifa*, in the UAE

2012

ABB successfully designs and develops a hybrid DC breaker suitable for the creation of large inter-regional DC grids

2013

ABB Review made available in e-reader format

Editors' picks

Treasures from the archives

Clearing the rails

Sarah Stoeter has a BA in English and Psychology from the University of Minnesota in the United States. She has been an editor for *ABB Review* since 2007.
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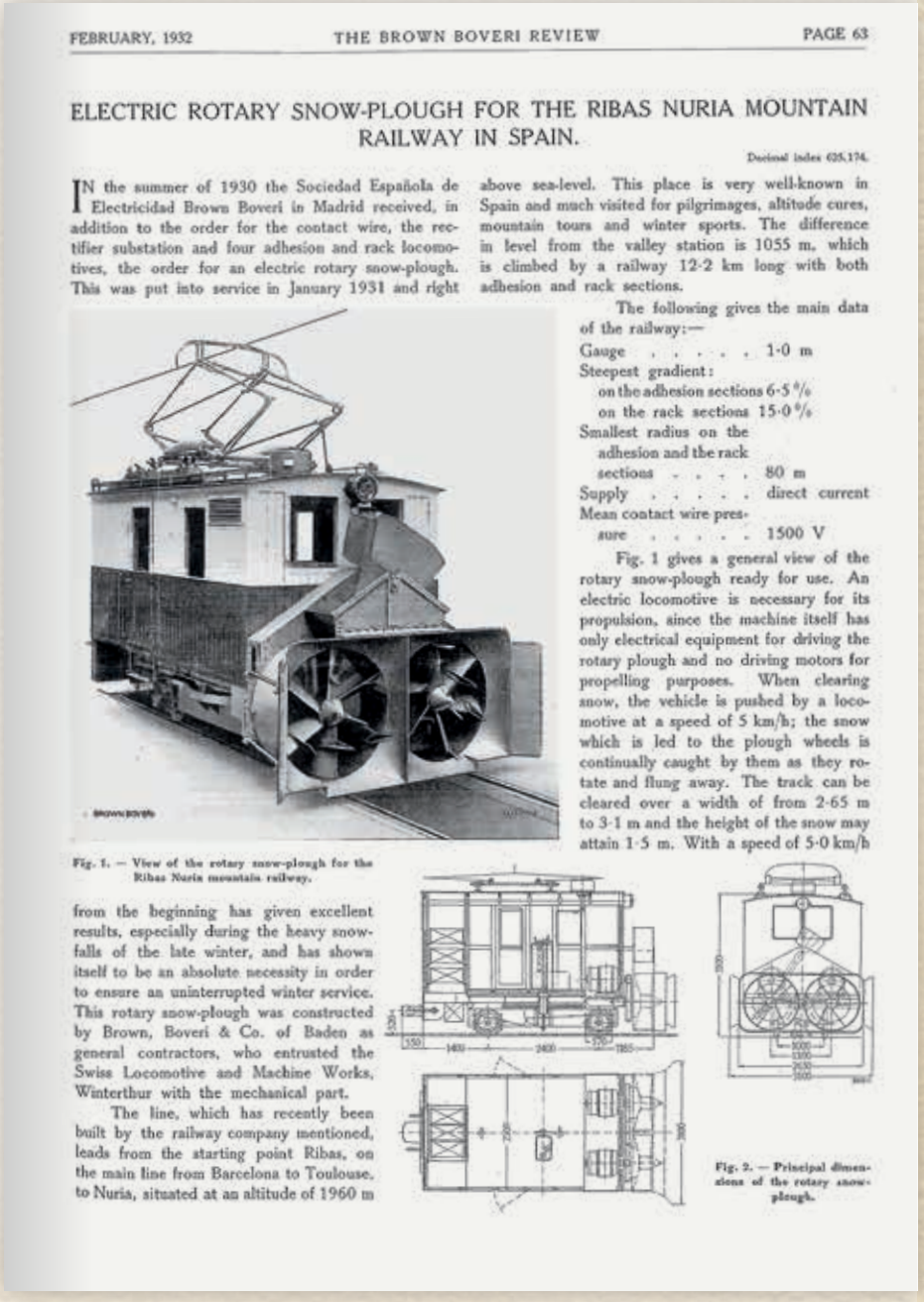
SARAH STOETER – If you're reading this journal, you are probably already well acquainted with ABB's countless power and automation technologies – industrial motors and drives, transformers, switchgear, robots, controllers, ship propulsion units, HVDC, and automation systems, to name but a few. But would you believe that, at one time, ABB made snow plows? This interesting twist in the company's history demonstrates to me the innovative spirit that is very much a part of ABB today. As an editor, it is a privilege to be able to help shape articles about technologies such as this one, to be part of ABB's innovative spirit.

ABB's predecessor companies, ASEA and BBC, both manufactured locomotives and were instrumental in the electrification of numerous railways particularly in Sweden and Switzerland. The electric rotary snow plow for locomotives, described in the 1932 *Brown Boveri Review* article "Electric Rotary Snow-Plough for the Ribas Nuria mountain railway in Spain," nicely complements the rail element of ABB's past.

A 12.2 km long railway, climbing 1,055 m from its valley station in Ribes de Fresser (Ribas) to Vall de Núria in the Pyrenees mountains at an altitude of 1,960 m above sea level, serviced an area "much visited for pilgrimages, altitude cures, mountain tours and winter sports" – a journey, which, in winter, would not be possible without a viable means of clearing heavy snow off the tracks. This was the impetus for the electric-rotary snow plow developed by BBC and SLM, which was put into service in 1931.

E. Hugentobler, (G.A.W.), "Electric rotary snow-plough for the Ribas Nuria mountain railway in Spain," *The Brown Boveri Review*, pp. 63–65, Feb. 1932.



FEBRUARY, 1932 THE BROWN BOVERI REVIEW PAGE 63

ELECTRIC ROTARY SNOW-PLOUGH FOR THE RIBAS NURIA MOUNTAIN RAILWAY IN SPAIN.

Decimal Index 625.174.

IN the summer of 1930 the Sociedad Española de Electricidad Brown Boveri in Madrid received, in addition to the order for the contact wire, the rectifier substation and four adhesion and rack locomotives, the order for an electric rotary snow-plough. This was put into service in January 1931 and right from the beginning has given excellent results, especially during the heavy snowfalls of the late winter, and has shown itself to be an absolute necessity in order to ensure an uninterrupted winter service. This rotary snow-plough was constructed by Brown, Boveri & Co. of Baden as general contractors, who entrusted the Swiss Locomotive and Machine Works, Winterthur with the mechanical part.

The line, which has recently been built by the railway company mentioned, leads from the starting point Ribas, on the main line from Barcelona to Toulouse, to Nuria, situated at an altitude of 1960 m above sea-level. This place is very well-known in Spain and much visited for pilgrimages, altitude cures, mountain tours and winter sports. The difference in level from the valley station is 1055 m, which is climbed by a railway 12·2 km long with both adhesion and rack sections.

The following gives the main data of the railway:—

Gauge	1·0 m
Steepest gradient:	
on the adhesion sections	6·5 %
on the rack sections	15·0 %
Smallest radius on the adhesion and the rack sections	80 m
Supply	direct current
Mean contact wire pressure	1500 V

Fig. 1 gives a general view of the rotary snow-plough ready for use. An electric locomotive is necessary for its propulsion, since the machine itself has only electrical equipment for driving the rotary plough and no driving motors for propelling purposes. When clearing snow, the vehicle is pushed by a locomotive at a speed of 5 km/h; the snow which is led to the plough wheels is continually caught by them as they rotate and flung away. The track can be cleared over a width of from 2·65 m to 3·1 m and the height of the snow may attain 1·5 m. With a speed of 5·0 km/h

Fig. 1. — View of the rotary snow-plough for the Ribas Nuria mountain railway.

Fig. 2. — Principal dimensions of the rotary snow-plough.

Worldwide wonderment

MICHELLE KIENER – They say that if you were to just glace at every piece of art in the Louvre in Paris, that it would take you nine months to see everything. My experience of visiting *ABB Review's* archives was very similar. I've worked for ABB, and read the *Review*, for 15 years yet if I chose to read all of the articles that I wanted to it would have to be my new full time job and it would probably take me beyond retirement age! There was so much fascinating material that it was extremely difficult to stick to the available research time.

Overall, the most striking thing for me was the global nature of both the *Review* and of ABB. It is normal these days to think globally, to cross an ocean in an afternoon, to talk of global reach and globalization, to send a "letter" which arrives on another continent seconds later. And yet the *Review*, as well as its preceding parent companies, ASEA and BBC, were global entities long before such buzzwords and high-speed travel and communications were common place.

In 2014, delivering massive hardware to customers still has its challenges, be they available and suitable transport, inclement weather or low bridges en route – all now coordinated and communicated via e-mail and smartphones. Even sending *ABB Review* around the world has its challenges, be they the array of import regulations or managing the global list of subscribers' which our team of 102 local country distributors have to stay on top of. So I can hardly begin to imagine what achieving the same end result would have been like 100 years ago. Imagine manufacturing, in 1914, a turbine in Switzerland that needs to be delivered to Australia. Imagine sending the commissioning staff there to install it and how long they would have been away from home and with no "local assistance" from Google or a lightweight dictionary in their smartphone. Imagine sending printed copies of the *Review* to different addresses around the world in a time when silent movies were still state-of-the-art technology.

That is why I have chosen to highlight the following article out of the thousands that I could have chosen. For me, it sums up perfectly the pioneering spirit, intrepid nature and "can do" attitude of all the many people that make up ABB, both now and in the past. And the *Review* has been an essential part of sharing their achievements, recording developments and documenting excellence.

Michelle Kiener studied electronics engineering at the Merchant Navy College, UK and has an MSc in environmental science. She has been an editor for the *Review* for four years.
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PAGE 108 THE BROWN BOVERI REVIEW FEBRUARY, 1931

NOTES.

Shipping large transformers.

Decimal index 656. 026:621. 314. 21.

Due to the increasing size of transformers, packing and conveying them to overseas destinations is accompanied by great difficulties to be overcome by both the designer and shipping company.

The most rational way of transporting the transformer is with the core and windings inside the oil-filled tank, while the insulator bushings, oil conservator, underframe and cooling equipment are sent separately. With this method the costs of erection are reduced to a minimum and the drying-out of the transformer on site is rendered unnecessary or else of shorter duration.

The weight of such a transformer when filled with oil, however, often exceeds the capacity of the cranes available on the ship or at the harbours, and the dimensions are greater than those permissible for bridges, subways, railway loading gauges and ships' holds.

In such cases the transformer must be partly or completely dismantled for transport, and the tanks of particularly large units are made in two, or even three parts. The upper part of the tank and also, if advisable, the upper yoke, are then packed separately. Instead of the dismantled top yoke, a temporary device for keeping the core and windings in place is used during transport.

As an example, the shipping of two large transformers to Melbourne (Australia) for Richmond Substation of the Victoria State Electricity Commission might be quoted. These are three-phase, three-winding 50-cycle transformers for outdoor erection, with external water and oil circulatory cooling. The following are some particulars referring to them:

No-load voltage: primary 120,000 V, secondary 22,000 V, tertiary 11,000 V

Rating: primary 31,000 kVA, secondary 37,500 kVA, tertiary 30,000 kVA

Fig. 1. — Transformer being loaded into a ship at Bremen by a floating crane.

Dimensions: Height (over terminals) 6·8 m; Length 4·7 m; Width 2·8 m

	net	gross
Total weight including cooling set but without oil:	66,500 kg	71,000 kg
Heaviest piece to be transported (lower part of tank with core, but without upper yoke and under-frame)	44,000 kg	44,000 kg
Weight of oil:	20,000 kg	

These transformers (see illustration inside front cover of this number) were made with two-piece tank and temporary pressing device for the frame and windings, in order to reduce to a minimum the total weight of the heaviest piece to be shipped (see above), while at the same time simplifying the erection on site as much as possible. Due

Fig. 2. — Transformer on the harbour crane while being unloaded at Melbourne.

Fig. 3. — Motor lorries for hauling the transformer through Melbourne.

Air heater for space research

ANDREAS MOGLESTUE – The archives of *ABB Review* represent a good cross section of the company's activities throughout the last 100 years of its history. While there are domains in which BBC and ABB have been active throughout this period, there are also product areas that have been discontinued or sold, and others again have been introduced through internal innovation or through the acquisition of other companies. Besides these, there are also articles dedicated to rare or one-off products engineered specifically for a particular application.

An article on an air heater for space research discusses an air heater that produces a hypersonic jet of air, able to heat air at 80 to 100 atmospheres to some 1,000 °C and blow it at Mach 12. This heater was produced by Tecnomasio Brown Boveri S.A. in Milan for the Centro Richerche Aerospaziali in Rome.

The 1968 *BBC Review* article discusses the engineering and testing of the heater, but only hints at the application. The Centro Ricerche Aerospaziali was at the time the aerospace research group of the University of Rome La Sapienza, and was working on a satellite launch program called San Marco. Italy launched her first satellite (San Marco 1) in 1964. This was one of the first-ever non-Soviet or US spacecraft. It was nevertheless launched from Wallops Flight Facility in Virginia, United States using a NASA Scout rocket and under NASA supervision. The satellite carried an ion probe to study the atmosphere and equipment to study the effects of long-range radio transmission.

In the following years, the Italians created their own rocket launching platform (also called San Marco) near Ras Ngomeni (Kenya) from which at least 27 rockets were launched between 1964 and 1988.

ABB still has involvement in space research today – for example through its Fourier transform infrared spectroscopy (FTIR), which is carried on satellites to study the atmosphere.

This brief insight into the back story of an otherwise seemingly random item of equiment is illustrative of the way ABB's achievements were often contributory to a broader context.

Andreas Moglestue studied electrical engineering at ETH Zürich. He worked for ABB Semiconductors and also developed software before joining the *Review* team.
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AN AIR HEATER FOR SPACE RESEARCH

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An air heater built by Tecnomasio Italiano Brown Boveri S.A. in Milan for experiments in the space research field has been successfully commissioned at the Centro Ricerche Aerospaziali in Rome. With this equipment a high-pressure air flow of 0·5 kg/s can be heated in a few seconds to a final temperature of some 1000 °C. As a result, the jet velocity at the exit nozzle from the duct is twelve times the speed of sound. This article describes the construction and test results.

The Problem

A VERY interesting and original application of an electric air heater has been developed by Tecnomasio Italiano Brown Boveri S.A. of Milan for the Centro Ricerche Aerospaziali in Rome. The heater is used to produce a hypersonic jet of air. The technical problems were considerable, owing to the exacting requirements to be met by the materials of the electrical part and of the sealing system, as these have to operate under extreme conditions.

Air at 80 to 100 atmospheres has to be heated to a temperature of some 1000 °C with the purpose of obtaining a maximum velocity at the exit from the convergent-divergent duct of about Mach 12, which is required for certain types of test.

The difficult question of selecting the correct heat transfer coefficients, which is a determining factor in sizing equipment of this kind, was accompanied by unusual problems of sealing and cooling.

Construction

The principles underlying the design of the air heater shown in Fig. 1 are essentially the same as those usually adopted for normal heaters, inasmuch as the air is brought into direct contact with the heating elements. These are spiral-wound and arranged longitudinally in the flow direction. They are of Kanthal alloy and located in channels in the refractory in a manner which is described more fully below.

The quality and shape of the refractory were the subject of detailed investigation and numerous laboratory tests in order to establish data on thermal expansion and the distribution of electric potential

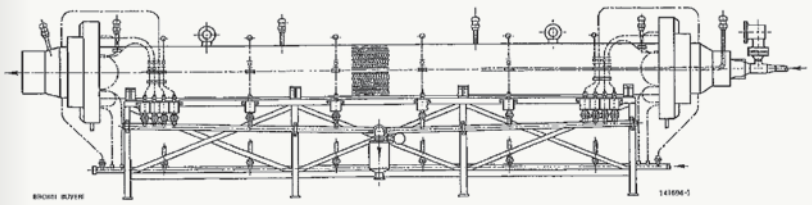


Fig. 1. – Diagram of air heater

Maximum heat output 600 kW, max. pressure 100 atm Maximum air flow rate 0·5 kg/s Maximum temperature 1250 °C

Rise of the robot

Celebrating 40 years of industrial robotics at ABB

DAVID MARSHALL, NICK CHAMBERS – In this centenary edition of *ABB Review*, one other important anniversary can be celebrated: It has been 40 years since ABB (then ASEA) introduced its first robot, the ASEA IRB 6, thus launching ABB's fascinating story in robotics. As the world's first all-electric, microprocessor-controlled, commercially available industrial robot, the IRB 6 was a historically significant machine. Since its launch, the field of robotics has changed drastically – almost beyond recognition. While many new and groundbreaking robotic developments have come along over the years, it is the technologies that have made robots easier to use and that have lowered the barriers to robot implementation that have made the biggest difference and accelerated the pace of robotic adoption.

The advances made in robotic technology over the past four decades have been astounding.

Industrial robots can now to be found in discrete manufacturing environments across the world. They increase productivity, ensure consistently high quality and improve workplace safety. The advances made in robotic technology over the past four decades have been astounding: Where once single robots performed relatively simple and monotonous tasks in hazardous environments, now multirobot synchronized systems deal with sophisticated assignments in flexible production cells. ABB has played a major role in driving this robot revolution.

Title picture
Robotics technology has progressed dramatically in the past four decades. In particular, robots have become much simpler to implement and use.

The first-ever industrial robot appeared in 1961 when a hydraulically driven "Unimate" was supplied to General Motors for tending a die casting machine. Hydraulics dominated robotics until, in 1974, the Swedish company ASEA (later to merge with Brown Boveri to form ABB) developed the IRB 6, the first all-electric, microprocessor-controlled and commercially available industrial robot → 1. This 6 kg payload capacity machine was unique, not only in its drive system but also in its anthropomorphic configuration and its innovative use of a microprocessor for accurate control. It set new standards in footprint size, speed of movement and repeatability, and gave rise to a number of imitators.

Hydraulics dominated robotics until, in 1974, ASEA developed the IRB 6, the first all-electric, microprocessor-controlled, commercially available industrial robot.

Spot welding soon became a prime application area and the IRB 90, launched in 1982, was designed specifically for this task. This full six-axis device, with integrated water, air and electrical feeds built into the arm, made

The most recent addition to ABB's range of painting robots is the compact and all-new IRB 5500 FlexPainter.

1 First IRB 6 customer – overview of cell

major inroads into the spot welding business.

Robots for painting

It did not take long for robots to move into the painting arena and, in 1985, ASEA released its first electric drive painting robot, the TR 5000. Later, in the 1990s, ABB invented the cartridge bell system (CBS) for painting car parts. The system utilizes easily replaced paint cartridges to reduce paint and solvent waste, thereby cutting costs and reducing emissions, while at the same time offering a wider choice in paint colors.

The most recent addition to ABB's range of painting robots is the compact and all-new IRB 5500 FlexPainter → 2. The unique design and configuration of the wall-mounted FlexPainter has created the largest and most flexible robot working envelope of any exterior car body paint robot. Two FlexPainter IRB 5500s can handle jobs that, until now, required four paint robots. The results are lower costs, both initially and in the long run, faster installation, high uptime and better reliability.

Robot mechanics

Such was the elegance of the IRB 6 design that its basic anthropomorphic kinematics with rotary joint movements can be seen in today's range of ABB robots. What has changed over the years is speed, accuracy and space efficiency.

Backlash-free gearboxes replaced ball screw drives for the "hip" and "shoulder" axes early on, resulting in better space kinematics. But the other significant change was the switch from direct current (DC) to alternating current (AC) drive motors, which are smaller, brushless (easier to maintain), more powerful and they have a longer life – all features demanded by industrial users.

Heavy-duty robots

Flexibility and adaptability are features constantly called for by robot users. In 1991, ABB met these demands head-on with the heavy-duty (150 kg payload capacity) IRB 6000. Aimed primarily at spot welding and large component handling, the IRB 6000 was built on a modular concept with a range of base, arm and wrist modules so that it could be optimized for each user's needs – a design philosophy that ABB still uses today. With features that appealed to a broad range of customers, the IRB 6000 was an instantly successful spot-welding robot. The newest model in this family, the IRB 6700, follows in the IRB 6000's footsteps as the highest-performance robot in the 150 to 300 kg segment. The IRB 6700 has a 20 percent lower total cost of ownership (TCO) than its immediate predecessor, the IRB 6640, thanks to a more robust design, longer service intervals and simplified maintenance. Reliability was a key design consideration for the IRB 6700 – it is designed for a mean time between failures (MTBF) of 400,000 hours. To achieve this level of reliability, each and every IRB 6640 failure report was analyzed and the lessons learned were used for the IRB 6700 design. With 15 percent less power consumption, it is also easier on the environment and on the utility bills.

2 IRB 5500

3 IRB 6700 with LeanID

Well dressed

The reliability of a robot's dressing – the cables and hoses that deliver air, electricity, fluids, welding wire, etc. to the end of the arm – is at least as important as the robot itself. In many cases, dressing wear is what causes the most service headaches. Swinging cables not only wear faster, but also limit the free movement of the robot. Fully integrated dressings (IDs) – ie, those internal to the robot – are costly and can be limiting in terms of what can be run through them. ABB's new LeanID achieves a balance between cost and durability by integrating the most exposed parts of the dress pack into the robot ➔ 3. This makes programming and simulation more predictable, creates a more compact footprint and, because wear and tear is reduced, lengthens service intervals. ABB's newest robot, the IRB 6700, has been designed to accommodate LeanID from the start.

Small is also beautiful

Sometimes robots have to be small. ABB's smallest-ever multipurpose industrial robot, the IRB 120, weighs just 25 kg and can handle a payload of 3 kg (4 kg for a vertical wrist) with a reach of 580 mm ➔ 4. A white-finish cleanroom ISO 5 (class 100) version, certified by the IPA (Fraunhofer-Institut Produktionstechnik und Automatisierung), is also available.

The IRB 120T variant is for rapid pick and place applications that require extreme flexibility combined with industry-leading 10 µm repeatability. The six-axis IRB 120T delivers a substantial increase in the maximum speeds of axes four, five and six, resulting in cycle-time improvements of up to 25 percent.

High-speed pick and place robots

ABB introduced the IRB 340 FlexPicker® robot in 1998 – another historically significant robot in that it was the first "delta-style" robot available for pick-and-place applications. It was capable of an impressive 10 G acceleration and 150 picks per minute, bettering human operators by orders of magnitude in both speed and versatility when handling small items, such as electronic components and food products.

The FlexPicker's software offers a combination of high-performance motion control with integrated vision guidance and conveyor tracking. The current standard model (IRB 360) is also available with longer arms and multiple payload capacities from 1 to 8 kg depending on needs, and a working range of up to 1.6 m ➔ 5. These new features enable the machine to perform pick-and-place actions over longer distances than ever before and also perform well even with heavy multiple item picks.

Such was the elegance of the IRB 6 design that its basic anthropomorphic kinematics with rotary joint movements can be seen in today's range of ABB robots.

Reliability was a key design consideration for the IRB 6700 – it is designed for a mean time between failures of 400,000 hours.

4 IRB 120 at ABB SACE in Frosinone

Palletizing

One application area for robots that has grown enormously in recent years is palletization ➔ 6. ABB's new IRB 460 is the fastest palletizing robot in the world. Compact, and with a lifting capacity of 110 kg, this four-axis robot is capable of up to 2,190 cycles per hour and so is perfect for high-speed end-of-line palletizing and bag palletizing. The IRB 460 has a reach of 2.4 m, occupies 20 percent less floor space and runs 15 percent faster than its nearest rivals.

Modern robot offerings extend far beyond the robot itself and the IRB 460, for example, comes with the PalletPack 460 Function Package. This is a set of pre-engineered products configured for end-of-line palletizing that greatly improves ease of use for integrators.

For high-output, full-layer palletizing, ABB has the IRB 760 robot. With a payload capacity of 450 kg and a reach of 3.2 m, this robot features high wrist inertia – double that of competitors – that enables it to rotate heavier and larger products faster than any other robot in this class. This superior speed makes the IRB 760 especially suited for palletizing full layers of beverages, building materials and chemicals.

Advances in control systems

In 1974, the IRB 6 control system had just a single 8-bit Intel 8008 microprocessor, an HMI with a four-digit LED readout and 12 punch buttons, and rudimentary software for axis interpolation and movement control. The robot required specialist knowledge to program and operate. Forty years and four control system generation changes later the picture looks completely different: IRC 5, ABB's fifth-generation robot controller, is specifically designed to make robots easier to use and lower the barriers to integration of robots into existing factories ➔ 7.

IRC5 offers superior motion control and rapid incorporation of additional hardware. Its motion control technology, featuring TrueMove and QuickMove, is key to the robot's performance in terms of accuracy, speed, cycle time, programmability and synchronization with external devices. QuickMove determines the maximum acceleration possible in any move and uses it on at least one axis so that the end position is reached in the shortest time. TrueMove ensures the motion path followed is the same whatever the speed and obviates the need for "path tuning" when speed parameters are adjusted online. Other features include ABB's well-known FlexPendant interface device with a touch screen and joystick programming, the flexible RAPID language, and powerful communication capabilities.

Recently, ABB introduced a compact version of the IRC5 for applications where footprint has to be minimized, but full IRC 5 functionality guaranteed.

5 IRB 360 in action

6 IRB 660 palletizing drums of paint

RobotWare is at the heart of the system and features a number of optional plug-ins designed to increase functionality and ease of use for robot users. For example, multitasking, transfer of information from file to robot, communications with external systems or advanced motion tasks.

A salient feature of IRC 5 is its MultiMove function, which allows control of up to four ABB robots plus work positioners or other servo devices – a total of 36 axes – in a fully coordinated manner.

Although complex, setting up and operating such a multi-robot cell with fully coordinated motions is made easier with the FlexPendant, the world's first open robot operator interface unit, developed for IRC5.

Next-generation robot safety

To ensure the safety of people working with industrial robots, humans and robots were traditionally separated by fences, and expensive safety equipment was necessary. ABB's SafeMove reduces the requirement for such equipment. SafeMove is an independent computer housed in the IRC5 cabinet that allows the reliable, fault-tolerant monitoring of robot speed and position, and the detection of any unwanted or suspicious deviation from the norm. If a safety hazard is detected, SafeMove executes an emergency stop, halting the robot within a fraction of a second.

FlexFinishing and force control

Another recent leap forward is ABB's FlexFinishing system featuring RobotWare Machining Force Control for delicate operations – specifically, for grinding, deburring and polishing castings. This unique robot application, first launched in 2007, contains a programming environment that allows the robot to find the optimum path itself. A feedback loop controls the speed and pressure of the tool.

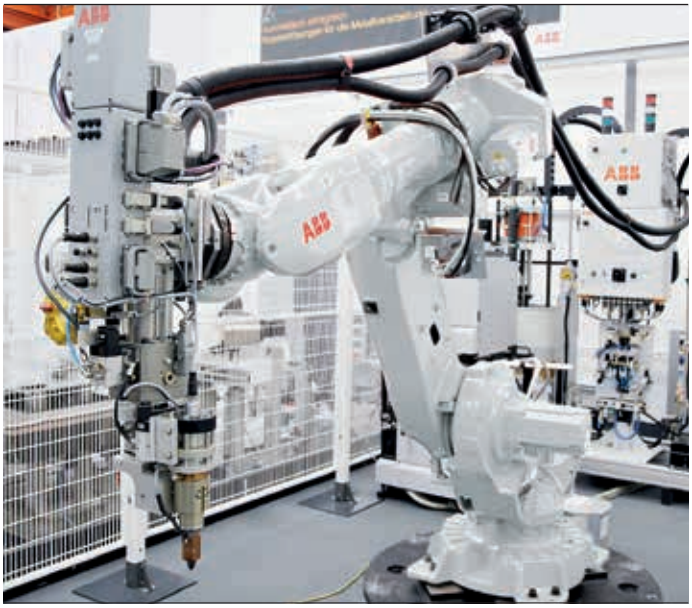
The application allows simple and efficient programming by using the force sensor to define the trajectory for the robot movement – the operator simply moves the robot by hand to teach it the rough path. The robot automatically follows the part, recording the exact path and generating a robot program.

This innovative approach not only improves the quality of the finished parts, but it also reduces overall programming time by up to 80 percent, reduces the cycle time of the robot by 20 percent and extends the lifetime of the grinding tools by 20 percent. Other function packages for precision work are available – for gluing, for example. The gluing package provides perfectly coordinated robot motion and adhesive dispensing with conveyor tracking. High precision and consistent robot-based gluing/dispensing not only enhances parts quality, but reduces cycle time, too ➔ 8.

ABB's new LeanID achieves a balance between cost and durability by integrating the most exposed parts of the dress pack into the robot.

7 IRC 5 controller

8 Gluing function package



Computer-based programming

Over the years, it has become clear that the easiest, fastest, most accurate and most flexible way to program robots is on a computer in the office before ever even touching any physical equipment in the real world.

This is the best way to maximize return on investment for robotic systems, resulting in lower costs, faster time to market and superior end products.

ABB RobotStudio allows programming to be done on a computer without committing to construction or disturbing existing production. It simplifies the process of programming robots and makes it easier to design solutions for complex production environments.

Among all computer-based robot programming solutions, RobotStudio is unique in that it is built on the ABB Virtual Controller, an exact copy of the real software that runs on ABB production robots. Using real robot programs and configuration files identical to those used on the shop floor ensures everything in the virtual world works exactly as it will in the real world.

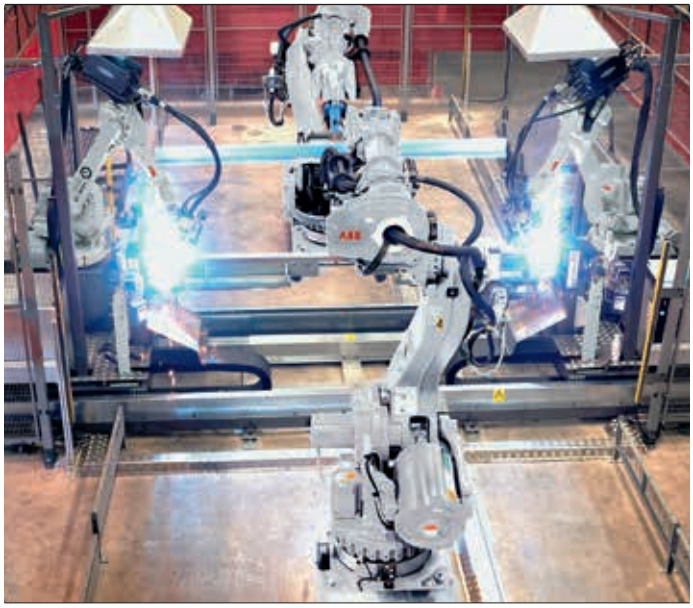
For developers, this method of programming is very efficient and can be done without time pressure or the constraints of pre-existing equipment locations. By lowering the barriers to robotic integration through ease of programming, customers and integrators both see reduced costs and faster times to market, resulting in a virtually instant return on investment.

Ready to go

Standardized manufacturing cells are removing some of the last barriers to the implementation of robotics. Instead of building robot cells from scratch, customers can use ABB's FlexLean concept, which offers a compact cell in which the robots, controllers and cabling are pre-mounted on a platform. FlexLean offers automotive manufacturers both geometrical assembly and respot cells that come with a choice of predefined configurations and a broad range of robotic products. This results in cells so cost-efficient that they can compete with manual labor in low-cost countries.

> The Flexpicker's software offers a combination of high-performance motion control with integrated vision guidance and conveyor tracking.

9 FlexArc – the complete welding package



10 Integrated Vision

An addition to the range of standardized cells is ABB FlexArc® – a complete arc welding package ➔ 9. It includes all the components necessary for robotic arc welding: Robots, IRC 5 with support for multiple-robot coordination, positioners and welding equipment. Customers can choose between several single- or multi-robot production solutions. All internal cables are routed and connected in the factory. Again, all cell components are mounted on a common base, eliminating the need for on-site engineering work. Software has been preconfigured for simple setup and operation. As a packaged solution, a FlexArc cell can be moved within or between different production facilities. This allows engineers to design highly flexible plant layouts that meet today's demands for rapid changeovers.

Robot eye

Even in the last decade, vision technology has progressed tremendously and ABB has recognized that a powerful vision-guided robotics system can help overcome many manufacturing challenges.

The ABB Integrated Vision product, which can be used in many industries, features 50 powerful vision tools, autofocus, integrated lighting and optics, faster image capture, capability to power and control a range of external lighting and enough input/output capacity for virtually any inspection scenario – all in a compact IP67 package ➔ 10.

Integrated Vision's extensive library of vision commands makes it easy to use – even for first-time vision users. ABB's offline 3-D programming tool, RobotStudio, offers, as standard, ready-made components for easy programming of the robot and the vision system.

Remote service

Reduced robot performance can significantly impact production. This is why ABB introduced remote service technologies and has now built up a global service with 1,200 service specialists in more than 50 countries and over 100 locations. ABB's installed base of more than 230,000 robots offers huge benefits of scale and means that world-class service can be provided at a reasonable cost. This aspect is one important market differentiator for ABB.

With remote service, robot data is sent from the controller to a service center for automatic analysis and scrutiny by a subject matter expert. The expert can remotely identify the cause of a failure and provide rapid support to the end user. Many issues can be solved without site visits. The automatic analysis can not only provide a failure alert, but can also predict future difficulties. At any time and from anywhere, a user can verify robot status and access important maintenance information about that robot system by logging into ABB's online MyRobot portal.

The age of the industrial robot

Since ASEA presented the first all-electric, microprocessor-controlled robot in 1974, industrial robotics has come a long way – and the pace of change is only accelerating. This year, ABB expects to sell its 250,000th robot and is primed to continue pioneering new developments, and building a comprehensive range of industrial robots, robot controllers, associated software and innovative service options. In 40 years, positioning accuracies have improved from 1 mm to 10 µm, user interfaces from a 4-digit LED readout to a full Windows touch-screen display and memory capacity from 8 kb to many terabytes. At the same time, reliability has increased enormously and costs have plummeted so far that, today, a robot costs less than half of what it did 10 years ago. The age of the industrial robot has arrived.

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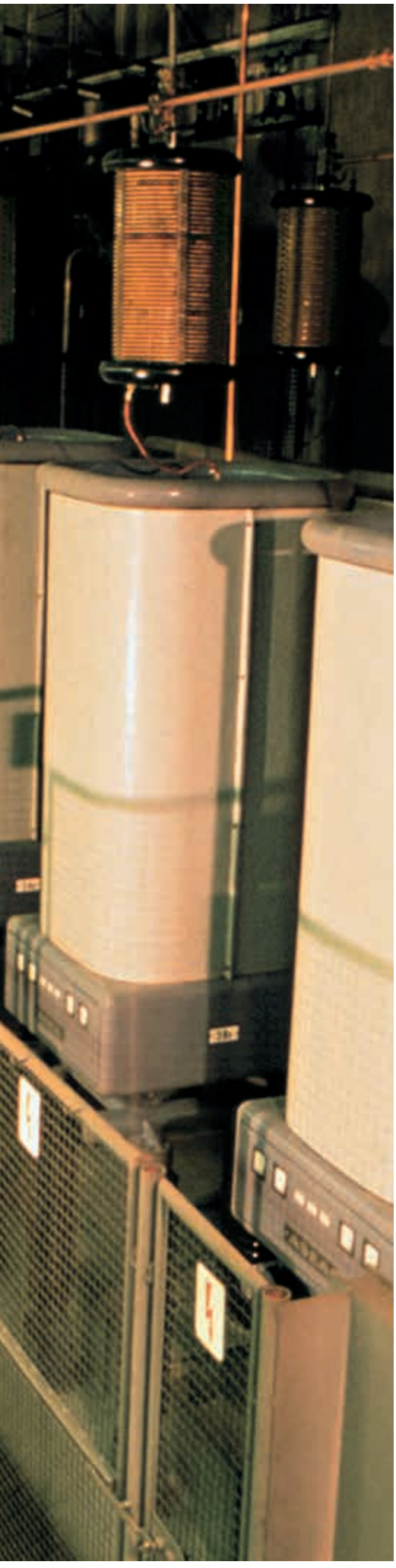


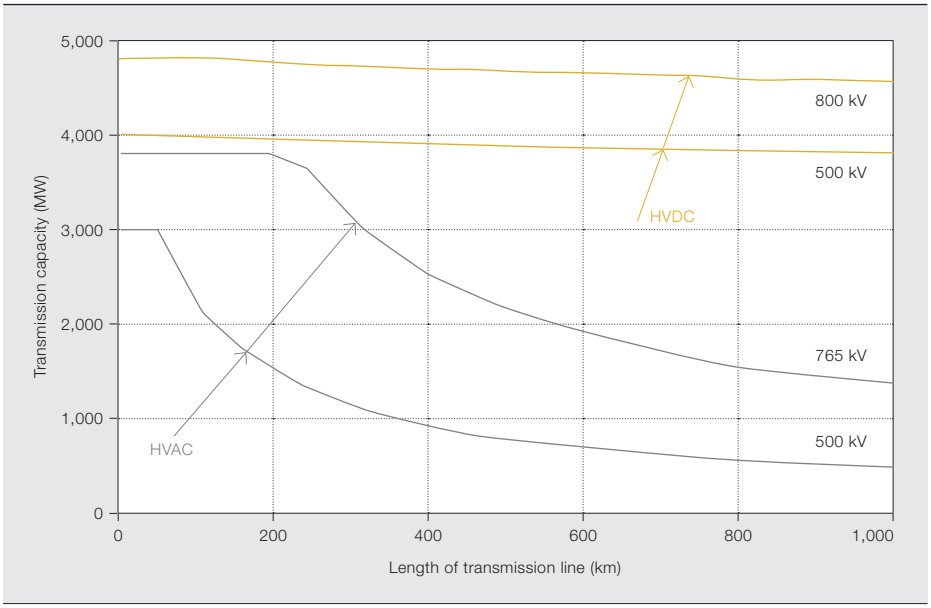
60 years of HVDC

ABB's road from pioneer to market leader

ANDREAS MOGLESTUE – Looking back on the clash between Edison's DC and Tesla's AC in the "War of the Currents" of the 1880s, it is often summarily assumed that the question was settled once and for all. But during the last 60 years, DC – at higher voltages than Edison could have imagined, has been making a steady comeback. HVDC is now an indispensable part of transmission grids across the world, and is set to expand into further markets still. The history of ABB is intricately intertwined with that of HVDC: ABB's predecessor companies pioneered the technology and ABB is not only firmly established as market leader today, but is the only company able to supply the complete scope of HVDC components, including the overall engineering as well as transformers, converter stations, semiconductors, cables and control systems.

Title picture
The world's first HVDC thyristor valves (foreground) connected in series with the original converter (background) at Gotland (circa 1970)

1 Reactive power limits the distance over which AC transmission is viable.



The transmission of electricity over large distances requires high voltage levels. Because ohmic losses are proportional to the square of the current, every doubling of the voltage reduces losses to one quarter. The simplest way of achieving high voltage levels is to use transformers. But unfortunately for the DC faction during the War of the Currents, the principle of transformation only applies to AC. DC's principal proponent, Thomas Edison, was however not one to give up easily. Rather than admitting defeat over this simple fact of physics, he resorted to a double-pronged counter-attack. On the one hand he drew attention to the safety hazards of higher voltages, sometimes resorting to horrific methods to instill public distrust of them (he once had an elephant electrocuted and also played a part in the creation of the first electric chair). As an alternative to high-voltage transmission, Edison promoted local generation. This meant providing a power plant in every neighborhood (the limit for the commercial transmission of 110 V DC being about 1.6 km). Although the urban pollution from such plants would have been problematic (especially considering the generation technology of the day), and the very suggestion may sound risible through the perspective of history, Edison's idea is enjoying some revindication at present through the concept of micro-generation – in which customers can feed self-generated electricity (eg, solar) into the grid.

The second prong of Edison's counter-attack was to try his own hand at transmitting electricity at higher voltages (seemingly in discord with his anti-high-voltage activism). In 1889, Edison built a 22 km line from Williamette Falls to Portland, Oregon (United States) transmitting about 130 kW at 4 kV. The voltage level was obtained through the series connection of generators (a principle that was first demonstrated at an exhibition in Munich, Germany, in 1882). Symptomatically with the demise of DC, the Oregon line was to be short-lived: It was heavily damaged by a flood in 1890 and then rebuilt as an AC installation by Edison's competitor, Westinghouse.

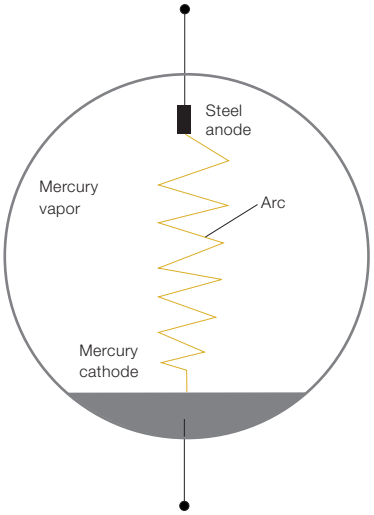
But the history of DC transmission did not end with that flood. As late as 2006 there were still 60 customers connected to the Edison DC supply in New York City (the supply was finally switched off the following year). But much more significantly, already during the inventor's lifetime, DC was growing in sectors such as rail transportation, aluminum smelting and telecommunications, in all of which it is still of great significance today. New applications added since include data processing and photovoltaics. However, in terms of transmission and distribution, AC's superiority appeared unassailable. But was it really?

Drawbacks of AC

Despite the rapid adoption of three-phase AC for transmission and distribution, longer AC lines face drawbacks. The most important of these is the phenomenon of reactive power. Reactive power is the flow of energy that continuously charges and discharges the line's electric and magnetic fields to accommodate the periodic oscillation of the line's voltage and current. Although not directly wasteful (the energy is recovered as the fields discharge), the additional current and voltage on the line subtract from its useful economic capability. As capacitance and inductance increase with the length of the line, reactive power also grows until a point is reached that commercial transmission ceases to be viable. It is ironic that the laws of physics that enable transformation and make high-voltage AC transmission possible in the first place are the same laws that ultimately limit the distance over which it is useful → 1.

Already during Edison's lifetime, DC was growing in many sectors.

2 Mercury-arc valve



3 Uno Lamm, the "father of HVDC," in the control room of the Gotland HVDC

There are solutions to the reactive power challenge – for example FACTS devices that compensate reactive power. However, DC transmission eliminates the problem entirely as the line's electric and magnetic fields are constant and thus only need to charged when the line is powered up.

Mercury-arc valves

Early attempts at DC transmission at higher voltages relied on the series connection of generators or motor-generators.[1] The principle was thus limited by mechanical constraints and was unable to economically compete with AC.

Interest in DC conversion resurged when a new technology came onto the scene: the mercury-arc valve.[2] This valve is a sealed bulb filled with mercury vapor using steel anodes and a mercury cathode ➔ 2. Once an arc is initiated between anode and cathode, the current flowing in the arc generates heat and ionizes the mercury vapor. At the interface of the arc and the mercury, the bombardment by ions causes electrons to be released. The steel can absorb electrons but does not release significant quantities at the operating temperature. Current can thus flow from the steel to the mercury but not in the reverse direction. The mercury valve thus displays diode functionality, making it suitable for AC to DC conversion.

But mercury valves can also perform the reverse (DC to AC) conversion: An artificial triggering of the arc (using an inductor to apply a voltage peak to an auxiliary electrode) permits conduction to commence at an arbitrary point in the cycle.

By being able to perform both conversions, mercury valves permitted the use of transformers, thus combining the transformation advantages of AC with the transmission advantages of DC.

The mercury arc valve was first demonstrated in 1902 by the American inventor Peter Cooper Hewitt. ABB's predecessor company, BBC (Brown, Boveri & Cie), was a leader in their development, with commercialization beginning in 1913. Early installations, however, did not target DC transmission but were used to rectify lower voltages (up to about 2,500 V) for industrial and transportation purposes.[3]

One of the problems encountered as voltages were increased was that of arc-back. An arc-back occurs when a reverse voltage across an unignited valve sparks

As capacitance and inductance increase with the length of an AC line, reactive power also grows until a point is reached that commercial transmission ceases to be viable.

Footnotes

1 A motor generator is a motor and generator pair sharing the same shaft. An array of motor-generators can be used to increase DC voltages by connecting the motors in parallel but the generators in series.

2 Mercury arc valves and ABB's part in their development are discussed in greater length in "From mercury arc to hybrid breaker" in *ABB Review* 2/2013, pages 70–78.

3 Nevertheless, BBC did demonstrate a temporary DC transmission in 1939. It transmitted 500 kW at 50 kV over 25 km between Wettingen and Zurich in Switzerland.

4 Schematic of the Gotland link, showing the series connection of converters in both stations

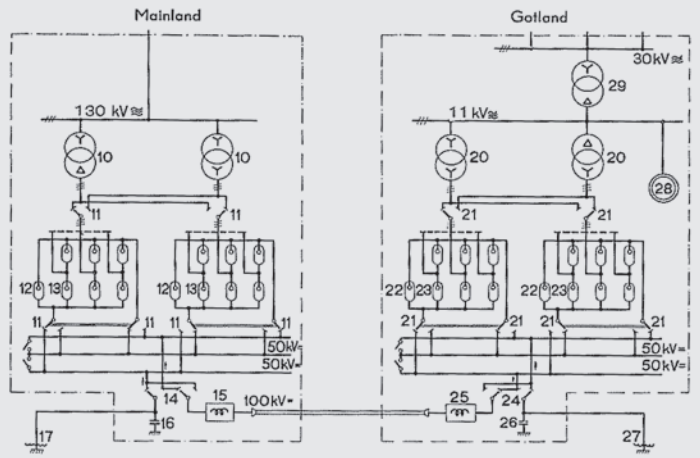
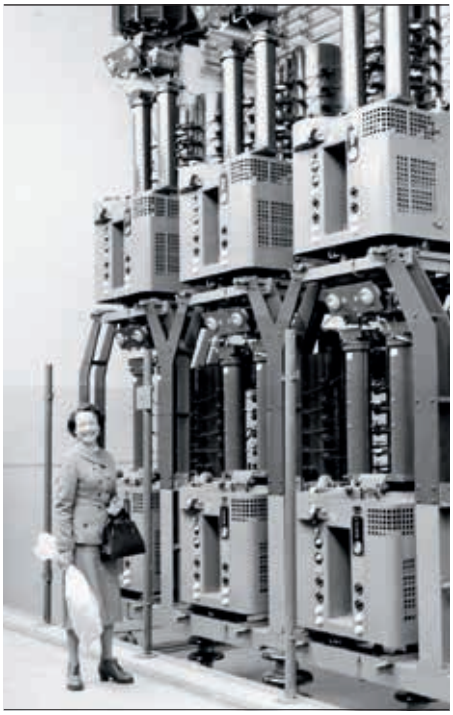


Fig. 1. Main circuits for high voltage D.C. transmission. (Tkh 7301)
10, 20. Three-phase transformers
11, 21. Double-throw isolating switches
12, 22. By-pass valve
13, 23. Six single-phase mercury arc valves
14, 24. Change-over switch
15, 25. Smoothing devices
16, 26. Capacitors for absorbing lightning surges
17, 27. Earth electrodes
28. Synchronous condenser
29. 11/33 kV three-phase transformer

The synchronous condenser (28) was to control reactive power and assure local commutation on the Gotland side (the link replaced a local power plant; there was thus no local commutation).

ASEA Journal, 1954, p. 142

5 The three valves of one converter of the Gotland link (with Lamm's wife, Pamela)



The Gotland link-provided many new challenges for ASEA, not least of which was the sea crossing.

an involuntary arc in the reverse direction. This not only causes a malfunction of the circuit but can cause permanent damage to the valve. It was another of ABB's predecessor companies, ASEA (Allmänna Svenska Elektriska Aktiebolaget) that was to provide the next breakthrough. In 1929, Uno Lamm ➔ 3 was awarded a patent for controlling arc-back by using grading electrodes. Grading electrodes are intermediate electrodes connected to a voltage divider to prevent an arc from being able to form from anode to cathode in a single strike. For this work and its consequences, Lamm is often called "the father of HVDC."

Despite this patent, the road from the basic idea to a reliable implementation was long. Due to the often unpredictable behavior of arcs, valve development was very much a process of empirical research. In order not to destabilize the electrical grid in the town of Ludvika (where the development lab was located) high-power trials had, at times, to be restricted to nightly hours.

The Swedish State Power Board (SSPB, now Vattenfall) followed ASEA's progress with interest. By the early 1940s, the technology was sufficiently mature for a trial converter station to be built. Trollhättan was chosen as the location for this (due to the adjoining power plant). Construction commenced in 1943, with operation beginning in 1945. A 50 km, 6.5 MW, 90 kV line was built to Mellerud, where another converter station was added. This transmission line was built purely for test purposes, a role it continued to fulfill until its decommissioning the late 1960s.

Gotland

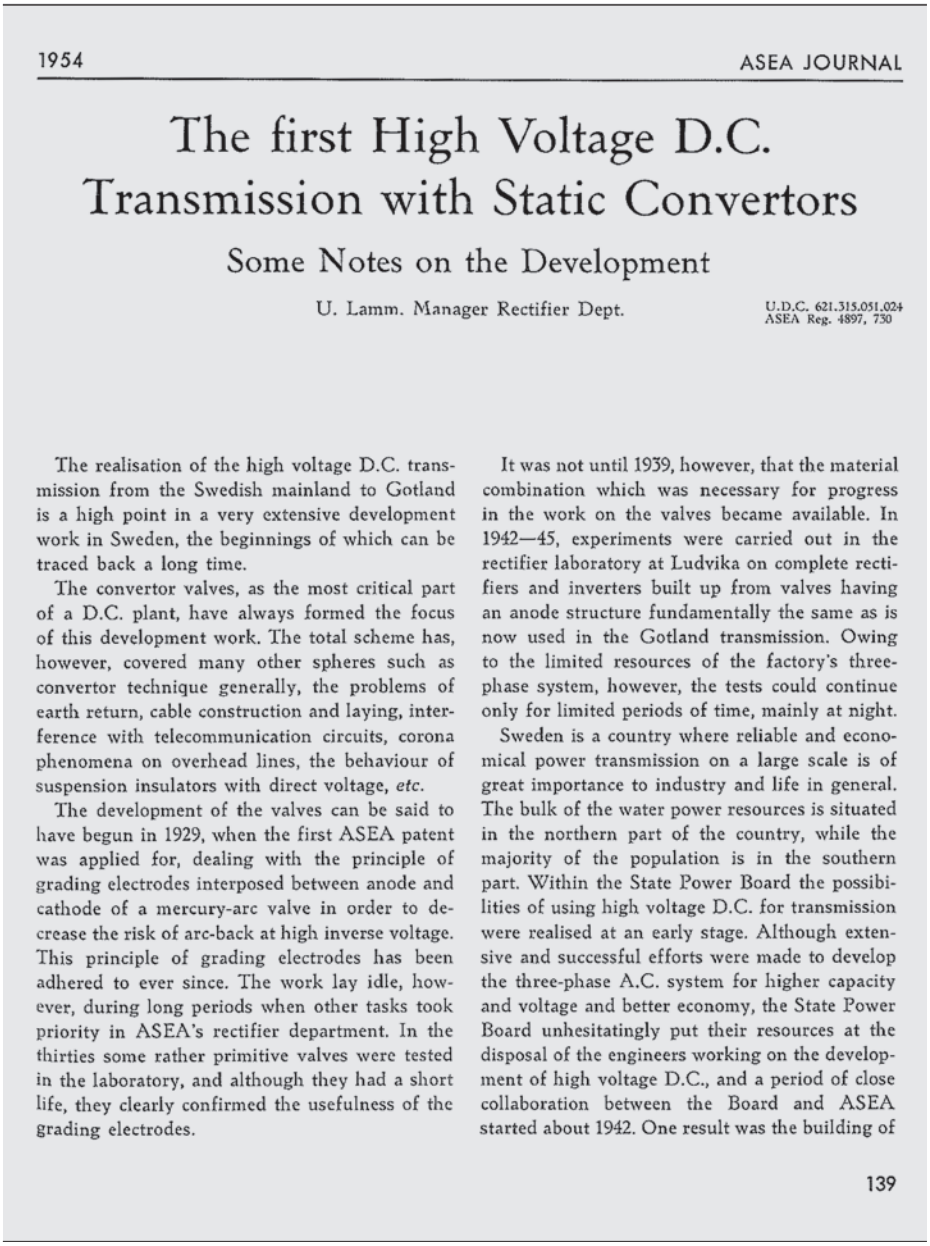
In 1950 Swedish parliament approved an HVDC link between the island of Gotland and the Swedish mainland ➔ 4 – 5. This link provided many new challenges for ASEA, not least of which was the sea crossing. For this purpose, an underwater cable was developed.

On March 7, 1954, the 200 A link was powered up, initially at 50 kV. This was doubled to 100 kV on July 26, when the second pair of converters were added in series. The era of commercial HVDC had begun.

The *ASEA Journal* marked the event with an article penned by Lamm himself ➔ 6. He opens with the words:

"The realization of the high voltage D.C. transmission from the Swedish mainland to Gotland is a high point in a very extensive development work in Sweden, the beginnings of which can be traced back a long time".

6 First page of Lamm's article from the *ASEA Journal* of 1954, presenting the Gotland link



1954 ASEA JOURNAL

The first High Voltage D.C. Transmission with Static Convertors

Some Notes on the Development

U. Lamm. Manager Rectifier Dept.

U.D.C. 621.315.051.024
ASEA Reg. 4897, 730

The realisation of the high voltage D.C. transmission from the Swedish mainland to Gotland is a high point in a very extensive development work in Sweden, the beginnings of which can be traced back a long time.

The convertor valves, as the most critical part of a D.C. plant, have always formed the focus of this development work. The total scheme has, however, covered many other spheres such as convertor technique generally, the problems of earth return, cable construction and laying, interference with telecommunication circuits, corona phenomena on overhead lines, the behaviour of suspension insulators with direct voltage, *etc.*

The development of the valves can be said to have begun in 1929, when the first ASEA patent was applied for, dealing with the principle of grading electrodes interposed between anode and cathode of a mercury-arc valve in order to decrease the risk of arc-back at high inverse voltage. This principle of grading electrodes has been adhered to ever since. The work lay idle, however, during long periods when other tasks took priority in ASEA's rectifier department. In the thirties some rather primitive valves were tested in the laboratory, and although they had a short life, they clearly confirmed the usefulness of the grading electrodes.

It was not until 1939, however, that the material combination which was necessary for progress in the work on the valves became available. In 1942—45, experiments were carried out in the rectifier laboratory at Ludvika on complete rectifiers and inverters built up from valves having an anode structure fundamentally the same as is now used in the Gotland transmission. Owing to the limited resources of the factory's three-phase system, however, the tests could continue only for limited periods of time, mainly at night.

Sweden is a country where reliable and economical power transmission on a large scale is of great importance to industry and life in general. The bulk of the water power resources is situated in the northern part of the country, while the majority of the population is in the southern part. Within the State Power Board the possibilities of using high voltage D.C. for transmission were realised at an early stage. Although extensive and successful efforts were made to develop the three-phase A.C. system for higher capacity and voltage and better economy, the State Power Board unhesitatingly put their resources at the disposal of the engineers working on the development of high voltage D.C., and a period of close collaboration between the Board and ASEA started about 1942. One result was the building of

139

ASEA's labs commenced thyristor development in the mid-1960s.

"The converter valves, as the most critical part of a D.C. plant, have always formed the focus of this development work. The total scheme has, however, covered many other spheres such as converter technique generally, the problems of earth return, cable construction and laying, interference with telecommunication circuits, corona phenomena on overhead lines, the behavior of suspension insulators with direct voltage, etc."

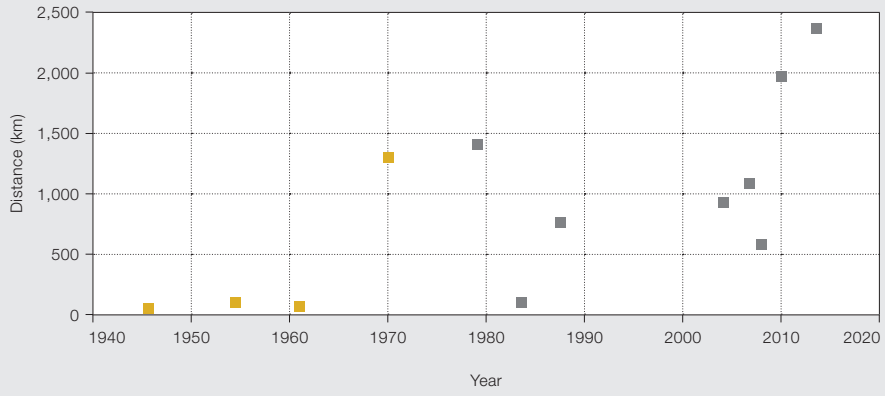
The latter paragraph would not look out of place in any publication on HVDC of the past 60 years: The basic principles established for Gotland still hold today, with ASEA (and later ABB) having built up expertise in all of the areas mentioned. In fact ABB is today the only company worldwide that is able to provide from a single hand all parts of an HVDC system, ranging from transformers, converter stations and their components, to the cables, control systems and more recently, breakers.

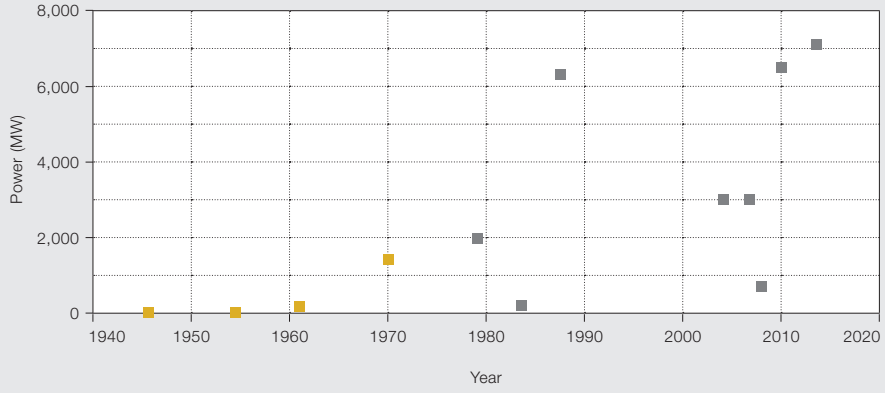
ASEA's second commercial HVDC project was a 160 MW link between Britain and France, inaugurated in 1961. Further projects, ranging from Scandinavia to Italy, Japan, Canada and New Zealand, followed in the 1960s, several of them again involving sea crossings using cables. The culmination of the development of mercury-arc based HVDC was the Pacific Intertie, a 1,300 km, 1,440 MW (raised to 1,600 MW in 1982), 500 kV link between Celio (Oregon) and Sylmar (southern

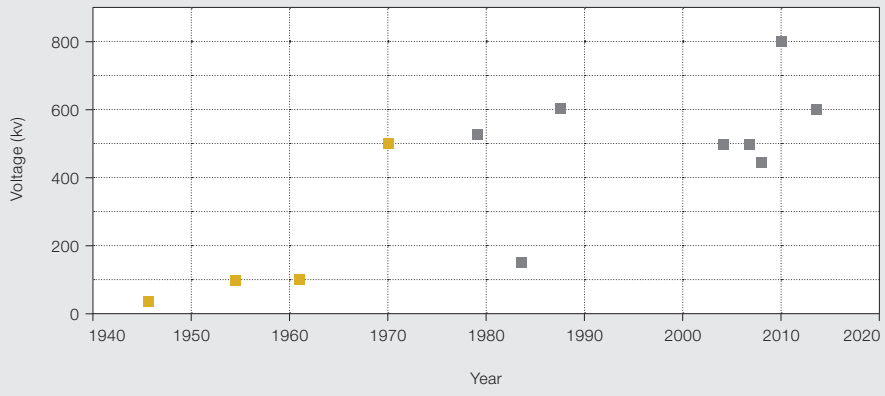
As an alternative to high-voltage transmission, Edison promoted local generation.

7 A selection from numerous HVDC projects delivered by ABB. The company has supplied more than half the world's 170 projects.

Year	Project	Converters	Distance (km)	Power (MW)	Voltage (kV)
1946	Trollhättan - Mellerud (test line)	Mercury-arc valves	50	6,5	45
1954	Gotland 1		98	20	100
1961	English Channel		64	160	100
1970	Pacific Intertie		1300	1,440	500
1979	Cahora Bassa	Silicon	1420	1,920	533
1983	Gotland 2		99	130	150
1987	Itaipu		780	6,300	600
2004	Three Gorges – Guangdong		940	3,000	500
2007	Three Gorges to Shanghai		1060	3,000	500
2008	NorNed		580	700	450
2010	Xiangjiaba – Shanghai		1980	6,400	800
2013	Rio Madeira		2375	7,100	600







8 An early ASEA thyristor-based converter

HVDC Light uses voltage source converters (VSCs) with IGBTs, a technology derived from that used in industrial drives.

California), built jointly with General Electric (GE) and inaugurated in 1970.

Until ceasing development of mercury-arc valves in 1971, ASEA had used them in links with a total power of 3,400 MW ➔ 7.

Thyristors

Commencing in the 1960s, a new type of valve came onto the scene, ultimately to displace mercury-arc technology ➔ 8.

The principle of the thyristor was first proposed by William Shockley in 1950. A thyristor is a semiconductor device with three terminals (anode, cathode and gate). As in a semiconductor diode, current conducts in one direction only, with a reverse voltage depleting charge carriers from the junction area. The thyristor has additional layers between the p- and n-zones that normally also prevent conduction, but the application of a trigger current to the gate floods this area with charge carriers and permits conduction. Once conduction is initiated, the production of charge carriers becomes self-sustaining and the gate current can be removed. Conduction does not cease until the main current falls below a threshold value. The overall functionality is thus broadly comparable to that of a triggerable mercury-arc valve, but with the advantage of being much more compact, having lower losses and eliminating the risks that come with handling mercury as well as being well suited to the series connection of multiple devices to create valves for higher voltages.

ASEA commenced thyristor development in the mid 1960s. In 1967 a test converter station was fitted to the Gotland link. In 1970, thyristor converters were added in series to the existing mercury-arc stations ➔ title picture, raising the operating voltage to 150 kV (while retaining the original cable, which had no trouble coping with the increased voltage.)[4]

HVDC projects delivered during the 1970s include the Skagerak link between Norway and Denmark, Inga-Shaba in the Congo, the CU project in North Dakota, United States, and Nelson River 2 in Canada.

During the mercury-arc era, ASEA had been practically alone in the market for HVDC, but the disruptive innovation caused by the greater simplicity of working with thyristors enabled many new competitors to enter the field. BBC, for example, teamed up with Siemens and AEG to supply the Cahora Bassa link between Mozambique and South Africa in the mid-1970s. ASEA responded to the new competition by investing in research to establish its leadership in HVDC thyristors.

A landmark project of the 1980s was the 6,300 MW Itaipu link in Brazil, awarded to a consortium of ASEA and PROMON, which was put into service in stages between

Footnote

4 The Gotland 1 link remained in use until 1986. Today the island is connected by two HVDC links, Gotland 2 and 3, commissioned in 1983 and 1987, respectively, with a total capacity of 260 MW.

As early as 1992, ABB proposed a grid of HVDC lines as an overlay over the existing power grid, relieving it of long-distance bulk flows.

9 The Jingzhou station of the Three Gorges Guangdong HVDC link

1984 and 1987. The 2,000 MW Québec – New England project delivered around the same time link was the world's first multiterminal HVDC link.

In 1988, ASEA and BBC merged to form ABB. In 1995, the company launched a new generation converter station. A key feature was the use of capacitor commutated converters (CCCs), permitting valves to be switched off rather than having to wait for a current zero crossing. This was the most fundamental change in switching since 1954, and permitted an improvement in controllability and reduction in reactive power. The first project to use this technology was the 2,200 MW Brazil – Argentina (Garabi) interconnection of 1999.

ABB continued to raise voltage and power levels. In 2004, the Three Gorges – Guangdong HVDC link (China) was opened, transmitting 3,000 MW over 940 km at ±500 kV ➔ 9. In 2007, a 1,060 km link of the same ratings connected Three Gorges to Shanghai. 2010 saw the Xiangjiaba – Shanghai ±800 kV, 6,400 MW, 1,980 km UHVDC (ultrahigh-voltage DC) link go into service. In 2013, the Rio Madeira link in Brazil began transmitting 7,100 MW over 2,375 km.

But HVDC is not just about ever larger power ratings spanning ever growing distances. Continuing in the tradition of the Gotland link, HVDC is also highly suitable for underwater connections, where it already displays advantages over HVAC on distances measured in tens of km (due to the higher capacitance of sheathed cables versus lines) ➔ 10. For example, in 2008, the NorNed link bridged the 580 km between Norway and the Netherlands.

Going light

On a smaller scale, HVDC can also be used to connect offshore windparks or supply power to oil and gas platforms ➔ 11. For the lower power classes, ABB introduced HVDC Light® in the 1990s. Rather than using thyristor valves, HVDC Light uses voltage source converters (VSCs) with IGBTs, a technology derived from that used in industrial drives. The higher controllability, reactive power control capability and black start capability of HVDC Light means it can be connected to island networks with no local commutation, but can also be used to relieve pressure on or stabilize existing AC grids. The compact design of HVDC Light means converter stations can be fitted inside containers and delivered to site in one piece, simplifying testing and commissioning.

The HVDC grid

Many new challenges face tomorrow's power grids. Not the least among these is the radical transformation of the generation landscape. Traditional power plants were mostly built close to the centers of consumption, but the rapidly increasing market share of renewables means that more and more power is coming from remoter regions. This power must be transmitted over long distances, often through areas where the traditional grid is weak and not suited to handle the extra load. As

10 Cable of the Fenno Scan HVDC link being loaded onto a ship. This link was completed in 1989.

11 Lifting an HVDC Light offshore module into position on a North Sea oil platform.

early as 1992, ABB's Gunnar Asplund proposed a grid of HVDC lines as an overlay over the existing power grid, relieving it of long distance bulk flows.

But building a DC grid is not as simple as it may sound. The main technical obstacle was the lack of a suitable breaker. In AC networks, breakers are used to quickly and safely isolate any section of line, for example in the case of a disturbance, without impacting the rest of the grid. When an AC breaker opens, an arc continues to conduct current between the contacts until the next zero crossing of the current. With DC not having such useful zero crossings, a different approach is required, and this has long prevented the development of more complex HVDC network topologies. ABB finally solved this conundrum in 2012. The hybrid breaker uses a combination of semiconductors and mechanical switches to break the DC flow in a safe and timely manner.[5]

DC or AC?

So, who really did win the War of the Currents? DC is advancing into areas that would traditionally have been AC applications, but it can never fully replace AC. Maybe, more than 120 years on, we can call it a draw: The history books of the future will give credit to both Tesla and Edison.

Footnote

5 See also "Breakthrough!: ABB's hybrid HVDC breaker, an innovation breakthrough enabling reliable HVDC grids" in *ABB Review* 2/2013 pp. 6–13.

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Pumping efficiency

A 100 MW converter for the Grimsel 2 pumped storage plant

HANS SCHLUNEGGER – Hydropower is one of the oldest forms of power generation and also one of the most flexible. Because water can be retained in a reservoir and released when needed, it is ideally suited for meeting demand fluctuations. When the mode is combined with pumped storage (meaning surplus electricity is stored by pumping water into the reservoir), its storage functionality can be expanded and it can furthermore be used in grid control by absorbing or generating the energy required to stabilize the grid. To operate more efficiently in pumping mode, the Grimsel 2 plant of Kraftwerke Oberhasli (KWO) – in the Bernese Oberland region of the Swiss Alps – has taken into service a 100 MW converter supplied by ABB.

Title picture
Kraftwerke Oberhasli is a complex of nine power plants located in the Bernese Oberland region of the Swiss Alps. The plants have a total generating capacity of 1,125 MW and an annual production of 2,200 GWh. The lakes have a combined inflow of 700 million m^3/year and a storage capacity of 200 million m^3.

At 100 MVA, the Grimsel 2 installation is the most powerful drive converter with DC link voltage delivered to date.

Pumped storage is used in what is called peak shaving: Energy is absorbed by pumping at times of low demand (typically at night) and the stored energy is converted back to electricity at times of peak demand. By mitigating the extreme peaks and troughs of the demand curve, pumped storage decreases reliance on other (often polluting) power sources required to cover peaks.

As well as bridging this classical day to night gap, pumped storage can also help integrate renewables: With more and more solar and wind power being fed into the grid, pumped storage can compensate for their unpredictability and variability, permitting consumers to continue using energy from renewable sources even when neither the sun is shining nor the wind blowing.

Moreover, moving beyond their strict mass-storage role, pumped storage plants also contribute towards grid control by producing or absorbing the relatively small amounts of power needed to more accurately balance supply and demand. To do this efficiently, the power needs to be regulated with high precision.

Grimsel 2

KWO's Grimsel 2 pumped storage plant in Switzerland ➔ 1 – 2 has four synchronous generators ➔ 3. Until recently, the plant's ability to regulate power depended on the starting up and shutting down of these individual units. When intermediate levels of power absorption were required, the difference could only be made up by running an additional unit in generator mode. Pumping and generating at the same time is not only an inefficient use of energy, but also wastes the plant's most valuable resource: its water.

To regulate the plant's power uptake more efficiently, KWO decided to equip one of the Grimsel 2 generators with a power-electronic drive. ABB won the order for this in 2010, with the installation being commissioned in 2013.

The converter

At 100 MVA, the installation is the most powerful drive converter with DC link voltage delivered to date ➔ 4. It is made of two units of 50 MW, each with its own input and output transformers ➔ 5, and is series-connected on both the generator and grid sides. Each of these converters in turn uses pairs of parallel-connected double-phase modules using IGCTs (integrated gate-commutated thyristors). The overall installation thus features 24 double-phase modules.

Pumping and generating at the same time is not only an inefficient use of energy, but also wastes the plant's most valuable resource: its water.

The unit's power is continuously variable between 60 and 100 MW (the lower limit is defined by risk of cavitation in the pump runner).

1 Grimsel 2 pumping-storage plant

Power in turbine operation	4 × 80 MW
Power in pump operation	4 × 90 MW
Average height difference	400 m
Water flow	4 × 22 m^3/s
Synchronous speed	750 rpm
Years of construction	1973-80

2 Grimsel 2: the lakes at a glance

	Name	Height above sea level when full (m)	Volume when full (106 m^3)	Surface area (km^2)	Greatest depth (m)
Upper reservoir	Lake Oberaar	2,303	58	1.47	90
Lower reservoir	Lake Grimsel	1,908	101	2.63	100

3 The Grimsel 2 plant has four synchronous generators.

4 The 100 MW converter

Starting

In turbine operation and in unregulated pumping mode, the machine set is started up with the turbine ➔ 6. The block transformer is magnetized by the generator and connected to the 220 kV level after reaching synchronization conditions. In regulated pumping mode, the block transformer and the two line-side converter transformers would have to be switched in directly, thereby causing very high inrush current peaks. To avoid this, the frequency converter DC link is energized by the start-up transformer through the converter diodes on the motor side. The transformers are then magnetized by the line-side converter and afterwards synchronized. The entire starting procedure takes only about 10 s, after which the machine is accelerated by the converter to 600 rpm with the watered pump operating against the closed spherical valve ➔ 6d. After opening the spherical valve, the speed is adjusted to approximately 690 rpm according to the minimum power required by the current operating head.

Power control

The active power is either set manually or by the higher-ranking plant control system, which adjusts the output of all KWO power plants to comply with the loading schedule. The line-side regulation setpoint is added to the loading schedule setpoint. The converter power and speed control are configured in cascade, the active power being limited by the current pumping head and the maximum converter power capacity.

Reactive power is regulated by a voltage control loop, set either manually or by the higher-ranking 220 kV line voltage control system. Active power takes preference over reactive power.

Operating modes

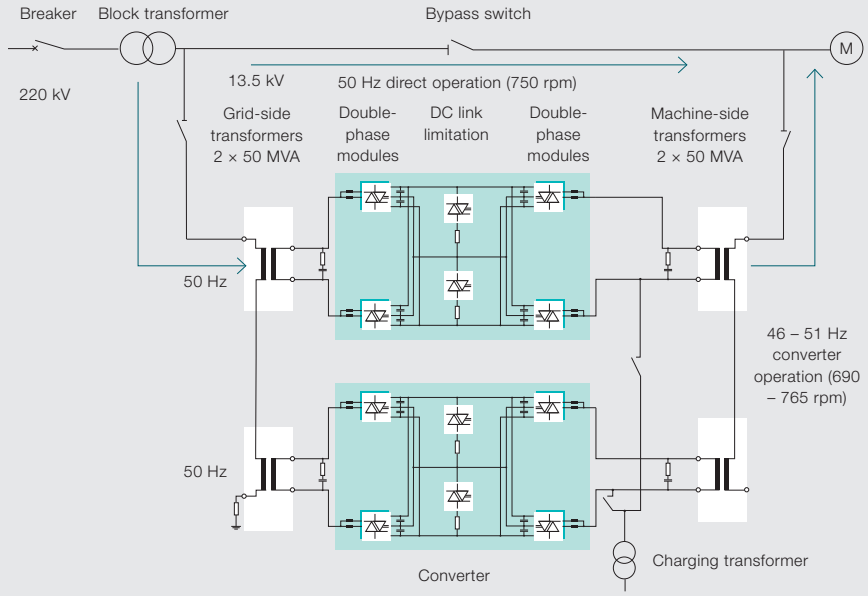
The following modes can be operated:
– Turbine
– Pumping without converter (constant rpm)
– Pumping with converter (variable rpm)
– Phase-angle correction using converter

Turbine operation with converter was not considered, because adjusting the Francis turbine speed to the relatively small head range would not compensate the converter losses.

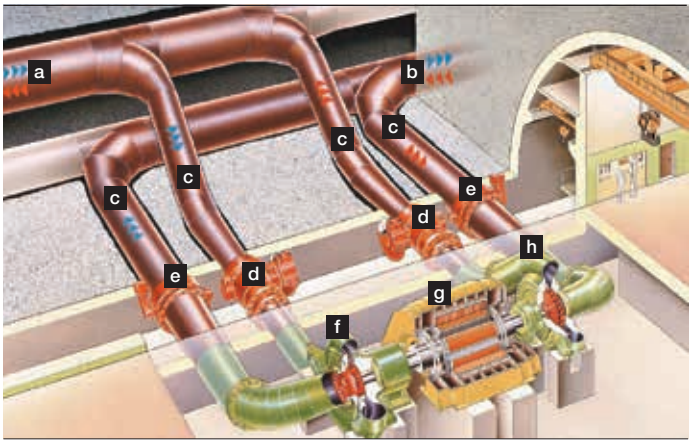
By the end of March 2014, the converter had provided 3,500 hours of controlled pumping and 850 hours of phase-synchronous condenser operation.

New pumped storage plants with pump turbines are almost exclusively equipped for variable-speed operation, using double-fed asynchronous motors according to the state of technology.

5 Schematic of the converter

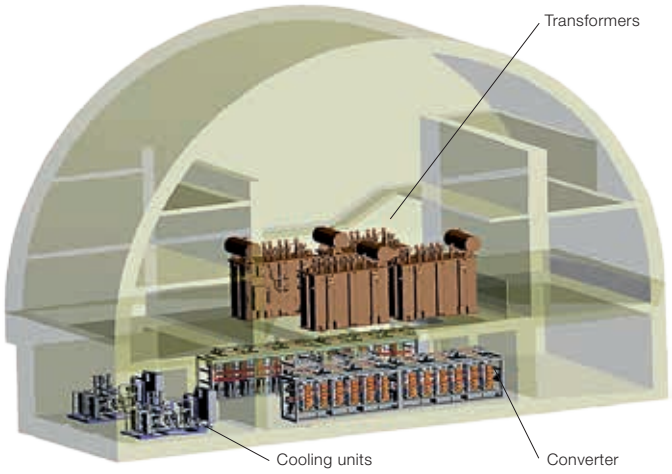


6 The turbine and its connections



a Pressure shaft to/ from Lake Oberaar
b Pressure shaft to/ from Lake Grimsel
c Connection pipes
d Spherical valve
e Throttle
f Turbine
g Pump
h Generator / motor
▸▸▸ Turbine operation
◂◂◂ Pumping operation

7 The machine-room cavern, with location of the transformers and converter.



Project execution

The converter delivery and erection schedule was adjusted to the refurbishing work taking place at the same time. This covered: overhaul of the hydraulic machinery, spherical valve and butterfly valve, renewal of the instrumentation and control systems, replacement of the turbine governor and excitation equipment, and replacement of the 220 kV switchgear.

Sufficient space was available in the existing cavern for the entire converter system ➔ 7–8. The four transformers were installed at machine room floor elevation and the converter units in the basement, where the cooling system connected to the existing plant cooling water network is also installed.

Operating experience

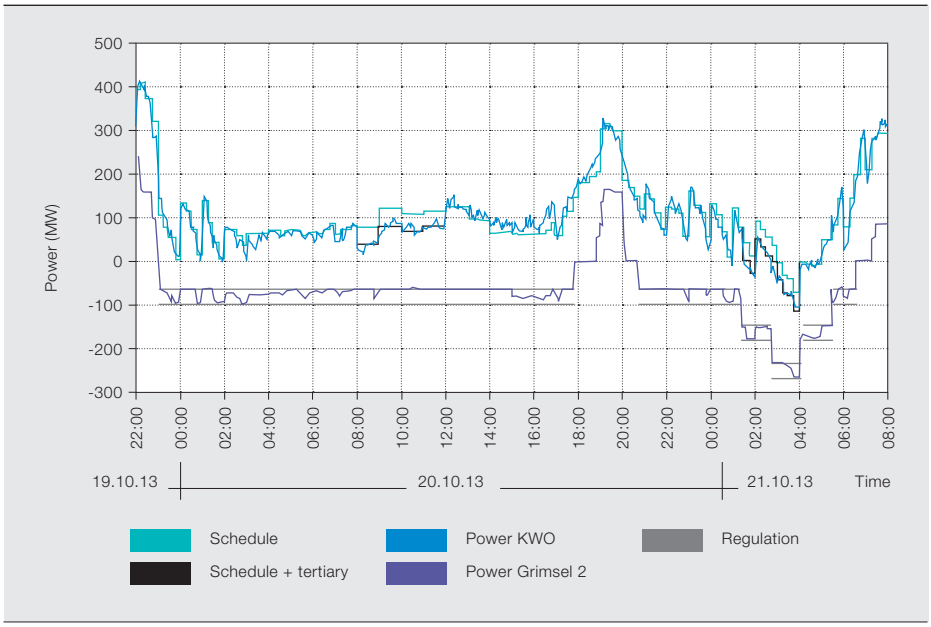
The installation has been in service since May 2013. By the end of March 2014 it had provided 3,500 hours of controlled pumping and 850 hours of phase-synchronous condenser operation ➔ 9.

Looking ahead

New pumped storage plants with pump turbines are almost exclusively equipped for variable-speed operation, using double-fed asynchronous motors according to the state of technology. There are serious drawbacks to this type of motor, however: The complex rotor is subject to

8 The 100 MW converter could be accommodated in the basement of the machine-room cavern.

9 The converter permits accurate regulation of the plant's power.



design limits that restrict speed increase to comply with the optimal speed of the pump-turbine. Furthermore, the starting procedure is much more complicated, sometimes even requiring pump-turbine dewatering, and compliance with Grid Code requirements is more difficult. For these reasons the trend in future will be more toward synchronous machines with full-size converters. Fitting an existing pumped storage plant with a full-size converter therefore offers an ideal way of testing this future-oriented technology in actual practice. Experience so far with the full-size converter at Grimsel 2 pumped storage plant is very promising. Despite progress with other storage technologies, pumped storage remains the only mature and affordable means of energy storage suitable for grid regulation, and thus has an important role to play in the generation landscape of tomorrow. The new converter at Lake Grimsel is a contribution to the Swiss Energy Strategy for 2050, which seeks to assure the continuity of the Swiss energy supply while increasing the use of renewables.

This article is adapted from "100 MW-Vollumrichter im Pumpspeicherwerk Grimsel 2" published in electrosuisse Bulletin 3/2014.

Despite progress with other storage technologies, pumped storage remains the only mature and affordable means of energy storage suitable for grid regulation.

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Unit of power

Cutting-edge motor design redefines power density

THOMAS EK, KARITA FORSS, TIMO HOLOPAINEN, JANNE IKONEN, OLLI LAHTINEN – ABB has introduced a new generation of motors based on the successful, high performance rib cooled motor range, type HXR. These new motors are named “High voltage rib cooled motors, NXR” and they achieve new levels of power density. The new motors feature improved internal and external cooling, cutting-edge coil manufacturing methods, a state-of-the-art frame design and unprecedented levels of adaptability and serviceability. The design offers a better solution for the wide range of applications in which totally enclosed fan-cooled motors are customarily used. The improvement in power density means that it will often be possible to use a motor with a smaller frame size to achieve the same output as previous, larger designs. Initially, the motors will be available in 355 and 400 frame sizes.

These motors are designed to become the new benchmark for the industry, while still complementing the existing range.

All rotating electrical machines generate heat as a result of the electrical and mechanical losses inside the motor. Losses are particularly high during starting and they also increase with increased loading. Cooling is, therefore, necessary to continuously transfer the heat to a cooling medium, such as the surrounding air. So important is cooling to motors that different cooling methods for rotating machines are officially defined in an IEC standard.

There has always been a demand from industry for motors to become more compact and, at the same time, deliver more power. This throws down the challenge to produce a motor design that is mechanically smaller and more powerful but that stays cool. This is not all: the motor should also operate within mechanical vibration constraints, be service-friendly and be flexible so as to simplify commissioning.

Perhaps the main innovation that contributes to improved efficiency is the motor's cooling system.

The new ABB motors described here are the result of a long period of research and development in which various parameters have been optimized to ensure that the motors will become the new benchmark for the industry, while still complementing the existing range. Not only do they produce more power per kilogram than previous designs, but they also have longer service intervals and more flexibility.

Innovative cooling

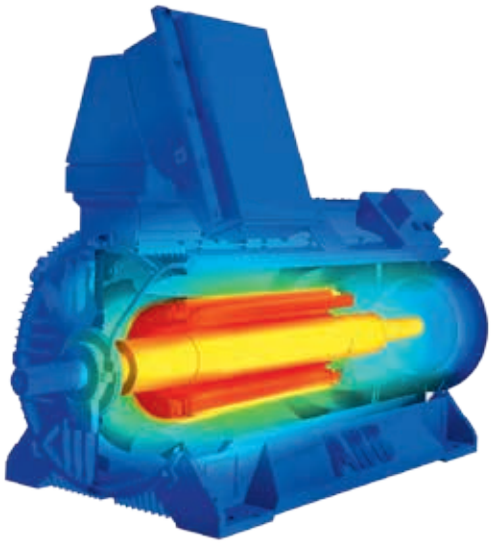
The innovation that contributes most to improved efficiency is the motor's cooling system.

Title picture

Optimized design of cooling, coils and casting allows more motor power to be packed into a smaller volume than before. And service and commissioning become easier too.

The coil has also been improved with better use of its active materials and re-dimensioning – making the coil more compact and thus increasing its power output.

1 Internal cooling as imaged by a thermographic camera



It is difficult to predict thermal efficiency, so the development team analyzed existing motors, constructed computational fluid dynamics (CFD) models, called in external partners to carry out simulations and developed analytical calculation methods that could be used to finalize the design. Further, the CFD models had to be both challenged with real measurements and interpreted correctly in order to turn the models and calculations into functioning motors. In this step, the expertise and experience of the ABB team and its partners played a crucial role.

ABB's innovative internal cooling system increases air circulation through the motor and routes air through channels in the stator and rotor, assisted by a fan → 1. An internal fan has been a feature of other ABB motors, but has never been so thoroughly exploited before.

ABB's innovative internal cooling system increases air circulation through the motor and routes air through channels in the stator and rotor, assisted by a fan.

The motor's end shields are designed to be both rigid and light, with an inner surface that facilitates internal cooling circulation. In addition, the interplay of the cooling channels and the external cooling areas have been optimized – for example, the air channels do not interfere with the rib cooling. While most motors have four air channels, the new motor has only three.

Upgraded cooling ribs

One way in which external cooling has been improved is with the increased number of cooling ribs. The ribs have also been lengthened and their pitch and angle optimized, with all obstructions reduced → 2. For example, the bolts and screws that hold the end shields in place are designed to not obstruct the air flow; a cable tray ensures that auxiliary cables are well stowed; the ribs are made so as to be easily cleaned; and the fixing points are positioned so that accessories are mounted on the side of the motor and do not affect the air flow. In addition to preventing obstacles to air flow, the outside ring of the end shield is finished with a 30 degree chamfer to direct the air more effectively.

2 Front view of the optimized rib construction

The ribs have been increased in number, lengthened and had their pitch and angle optimized, with all obstructions reduced.

The research carried out to optimize the cooling process is also of benefit when it comes to the modeling required to customize individual motors: Full-scale CFD modeling can take hours or even days but parameters from the CFD modeling and measurements can be extracted to allow the rapid calculation of temperature change for a particular motor design. More accurate temperature predictions mean that motors can be tailored precisely to their requirements, thus ensuring better performance.

Lowering vibration

The new, more powerful motors are longer than their predecessors and this has necessitated further work to ensure that their greater length does not result in more vibration. Here, too, designs were developed using computers, but the virtual prototyping – in this case the finite element method (FEM) – was unable to satisfactorily predict the characteristics of the new design. So, components such as the rotor, the stator and the end shields were modeled and manufactured. The manufactured components were then measured and the FEM models were validated against the measured data of each component. In an iterative process, these two were validated against each other until the most effective designs could be identified. The final design avoided all the significant resonances that may be caused by mechanical and electrical excitations → 3.

Increased rigidity reduces vibration. One way to increase rigidity is to increase the axial and transverse dimensions of the mounting holes. More important for the rigidity, however, was the optimization of the mechanical design.

The objective of this optimization was to reduce the use of material while still complying with the vibration requirements of the main industrial standards. In the past, rigidity would have been achieved by simply adding more metal. This solution is no longer acceptable – strength and rigidity have to be achieved by the intelligent shaping of the material and not by extra mass. But the design of the various elements of a motor is not an exact science. For example, the panel between the feet serves two purposes: It houses one of the three air channels and also provides rigidity to help transfer the horizontal forces from the stator to the feet. Calculating the best size for the air openings at either end on the inside of the air channel or the optimum thickness of the cast iron is not straightforward, especially if the amount of material and the weight of the motor are meant to be reduced. The development teams worked with suppliers to achieve a casting process that met design requirements and optimized the use of material.

One of the aspects that was considered in the modeling of this new motor was how it would function on different foundations – since problems with vibration

The research carried out to optimize the cooling process is also of benefit when it comes to the modeling required to customize individual motors.

3 Modelling of rotating electromagnetic traction to predict mechanical vibrations

are often caused by the interaction between the motor and the foundation on which it stands. It makes a considerable difference whether a motor is mounted on a concrete block or on a steel skid. The new motor can be used with a wide variety of foundations.

New coil manufacturing

The coil has also been improved, with redimensioning and better use made of its active materials. Making the coil more compact increases its power output. New tools have been developed that allow better control of coil-end shaping in the manufacturing process, which has improved quality and repeatability so that every coil is now closer to perfection than was previously possible.

The new coil manufacturing process is already having an influence on production methods in other ABB motor ranges.

Flexibility of deployment

One of the most immediately noticeable innovations is the option of fitting the main terminal box on either side or on either end of the motor. In the case of the 400 frame size, it can also be fitted in the middle. Changing the position of the box simply involves exchanging it for the hatch that covers the desired position → 4.

The mounting of the auxiliary terminal box is also extremely flexible – it can be fitted on either side of the motor and in several locations along its length.

Improved cooling ensures that the motors will last longer and require servicing less frequently because lower temperatures in the bearings will mean less frequent lubrication.

Thus, a change of factory layout does not mean that a new motor needs to be bought merely because the power comes in from the side opposite the cable connection. And, especially in industries where motors are used on either side of a production line (metal or paper industries, for example), one spare instead of two can be enough to meet backup needs. There is no need to send the motor in for modifications – ABB service personnel can do all the work on-site.

A wide range of options is built into the basic design and this type of flexibility helps to improve lead times. For instance, the end shields are pre-engineered to accommodate accessories like

4 Flexible deployment

The final design avoided all the significant resonances that may be caused by mechanical and electrical excitations.

the waste grease box and instrumentation, allowing faster and easier customization.

Serviceability

Improved cooling ensures that the motors will last longer and require servicing less frequently because lower temperatures in the bearings will mean less frequent lubrication.

To ensure that any problems are dealt with early, the new motor can also be equipped with ABB's condition monitoring system, ABB MACHsense-P, or its remote monitoring system, ABB MACHsense-R. The motor includes provisions for the installation of sensors and, for ABB MACHsense-R, fixing points for a monitor.

Additionally, it is now possible to examine the coil ends without removing the bearing shields. The bearings themselves can be examined with an endoscope and without removing the bearing shields.

All this helps to increase reliability and decrease costs.

More power and know-how per kilo

The innovations in the new motor (type designation NXR) mean that it can often provide the same output power as a motor one, or even two, frame sizes larger. In extreme cases, this can result in a weight reduction of 40 percent.

These new motors embody more than 100 years of ABB's experience in the field combined with the latest design and manufacturing technology. Also, the developments described benefit more than just this range of motors: Already the new coil is being used elsewhere in ABB – and the new cooling developments will almost certainly have an influence on other cooling designs. The calculation tools, which are derived from virtual prototyping and confirmed by validation measurements on actual prototypes, look set to be adopted within ABB.

The new range of motors, which currently targets 355 and 400 frame sizes, will soon be extended to include other frame sizes and additional features.

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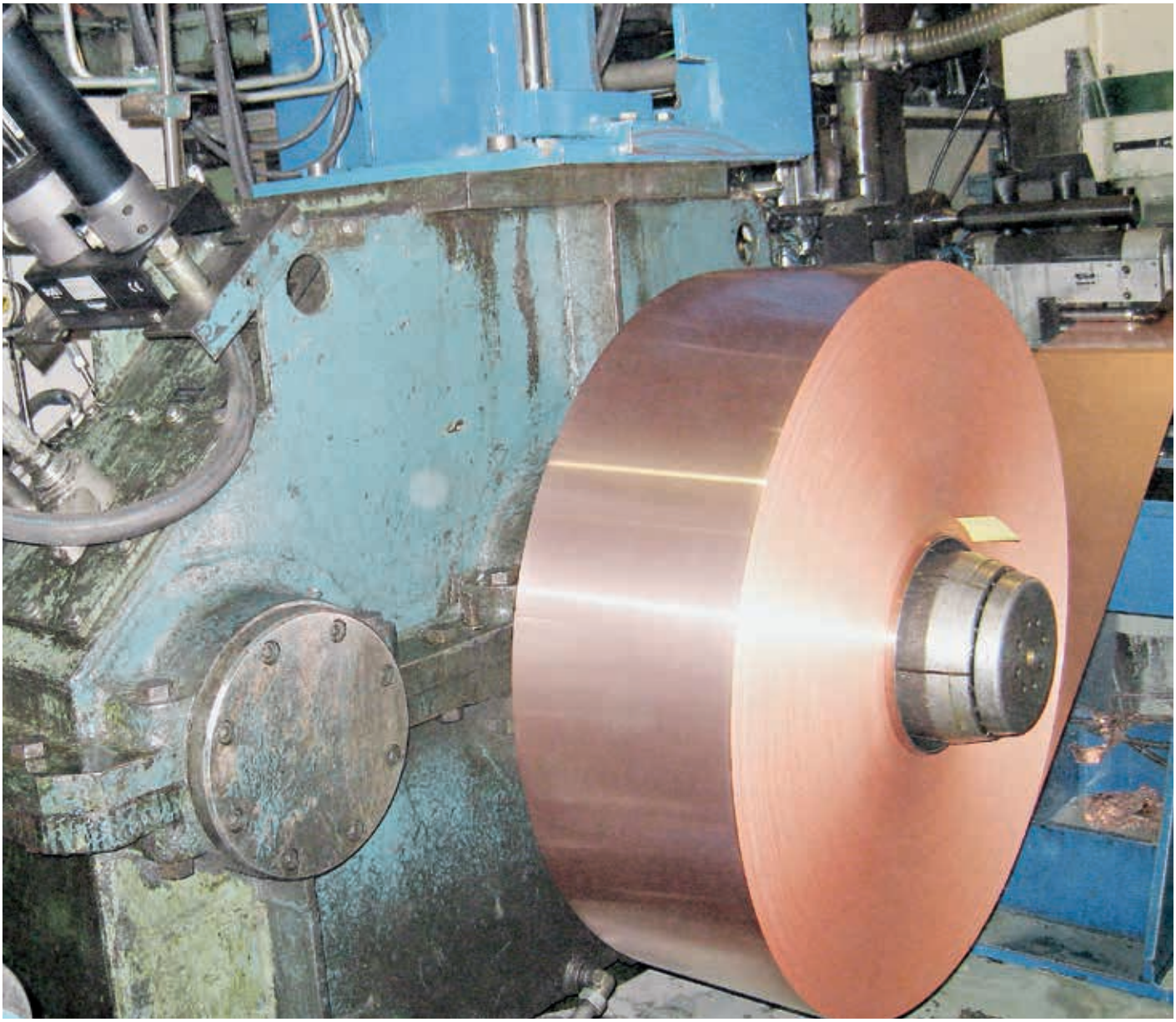
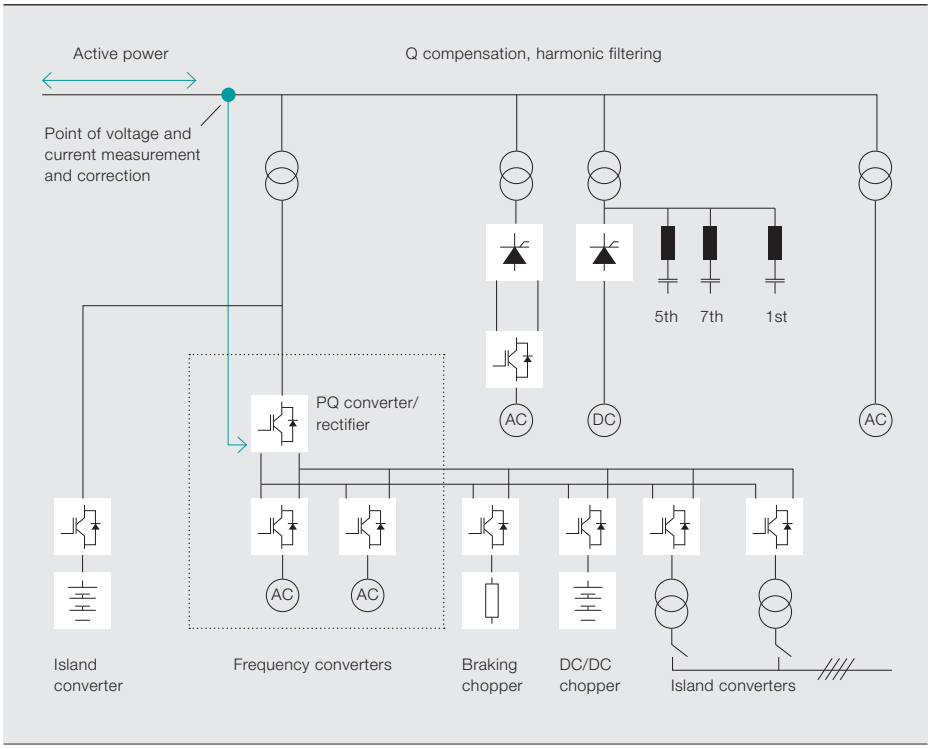


Multitalented

ACS800 power electronics can do more than rotate a motor

REIJO KOMSI – Industrial drives turn, literally, the wheels of commerce. That makes drives and the technology that controls them very important products in the industrial setting. Where several drives form part of a single process, as in a paper machine, say, and the individual drive motors have to be coupled in some way, it makes sense to use one so-called multidrive to manage all of them. ABB's ACS800 multidrive is one such device. The ACS800 contains sophisticated software and power electronics that handle the power flow to the drive. However, with appropriate application software, the power electronics module is capable of far more than just rotating a motor. For instance, it can perform valuable power quality correction and enable the power electronics to support intentional islanding.

1 A standard ACS800 multidrive schematic. Island converters, a braking chopper, a DC/DC chopper and energy storage can also be configured.



The multidrive approach has been very successful throughout industry. Instead of many individual drives being driven separately, products such as ABB's ACS800 multidrive handle multiple drives and allow coupling between them. This is important in processes like papermaking where many drives have to be tightly coupled to ensure good product quality all the way through the production process. These, and less-tightly coupled, applications benefit from the other advantages of the ACS800 multidrive approach too, such as space savings; savings in cabling, installation and maintenance costs; reduced component count and increased reliability; and the implementation of overall safety and control functions made possible by the common supply of the ACS800 multidrive.

The ACS800 multidrive has a rectifier unit and two or more frequency converters connected to a common DC link ➔ 1. The most sophisticated type of rectifier unit is an IGBT (insulated-gate bipolar transistor) supply unit (ISU), which consists of an active power stage similar to that of the frequency converter. This is capable of bidirectional active power flow, which enables regenerative energy from braking to be fed into the grid. In addition, the harmonic distortion of such an active rectifier is much lower than that of a diode or thyristor rectifier.

The fundamental building block of the rectifier – six IGBTs and six freewheeling diodes – can be used for other purposes by implementing appropriate software. This article describes two of these: power quality (PQ) correction and intentional islanding.

Power quality correction

The PQ correction abilities of the unit enable reactive power compensation and active harmonic filtering. Four of the most significant characteristic harmonic currents – the fifth, seventh, eleventh and thirteenth – can be filtered ➔ 2.

PQ correction is available at the same time as the unit is supplying active power for the motor drives. The voltage and current measurement and correction point can be on the low-voltage (LV) or medium-voltage (MV) side – whereby the latter is more beneficial because it takes the reactive power of the transformer(s) into account. A dedicated board performs voltage and current measurement. The analysis, reference generation and control is then performed internally and no communication is needed with the external automation ➔ 1.

The PQ correction can also be used in parallel with passive filters as a kind of hybrid compensator. This requires less total investment, but the performance is still as good as with full active correction.

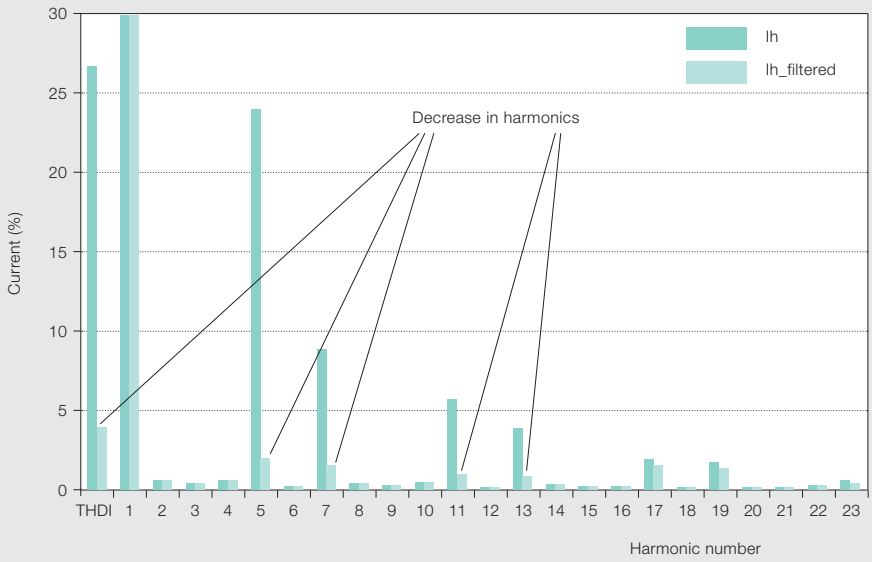
Compensating reactive power and harmonic currents can reduce MV currents significantly – 45 percent in one reference case. This means lower stress in MV transmission lines and transformers, higher cosphi, lower levels of harmonic distor-

The fundamental building block of the rectifier can be used for other purposes by implementing appropriate software.

Title picture
ABB's ACS800 provides sophisticated control of industrial motors, such as the one shown here. But the ACS800 power electronics can be used for other tasks, too.

The PQ correction abilities of the unit enable reactive power compensation and active harmonic filtering.

2 Reduced harmonics



tion and an increase in MV line loading capacity. The decrease in reactive power can be directly equated to savings in the electricity bill. In addition, lower reactive power leads to lower voltage variation and, thus, lower flicker index.

Intentional islanding

The other control software discussed here enables the ACS800 power stage to be used as an island converter – ie, to produce robust sinusoidal three-phase voltage, similar to a rotating generator, for the process. Intentional islanding is the deliberate sectionalization of the power system during disturbances to create power "islands" that maintain a continuous supply of power to a critical process.

The energy required for this can come from any DC source: eg, a rectified AC grid, wind turbine, diesel generator, solar cell, fuel cell or battery bank. The battery storage can be connected straight onto the DC link or through a DC/DC chopper. The common DC link makes distribution of power to the process drives straightforward. This same concept can be utilized in smart grid applications where no transmission lines are available but there is a need for electricity to provide power "islands." In smart grid applications, the battery energy storage is essential for balancing the distributed generator production and the island grid consumption → 3.

Usually, emergency power (from batteries) is required to ride through a supply grid fault or to buy time to start diesel backup generators. Energy storage dimensioning depends on the topology used, actual power required and reserve time.

The energy storage can also be used to balance the active power intake from the grid if the industrial process is very dynamic. The benefit of using energy storage in a dynamic process is that a smaller rectifier unit can be used, due to the lower peak power.

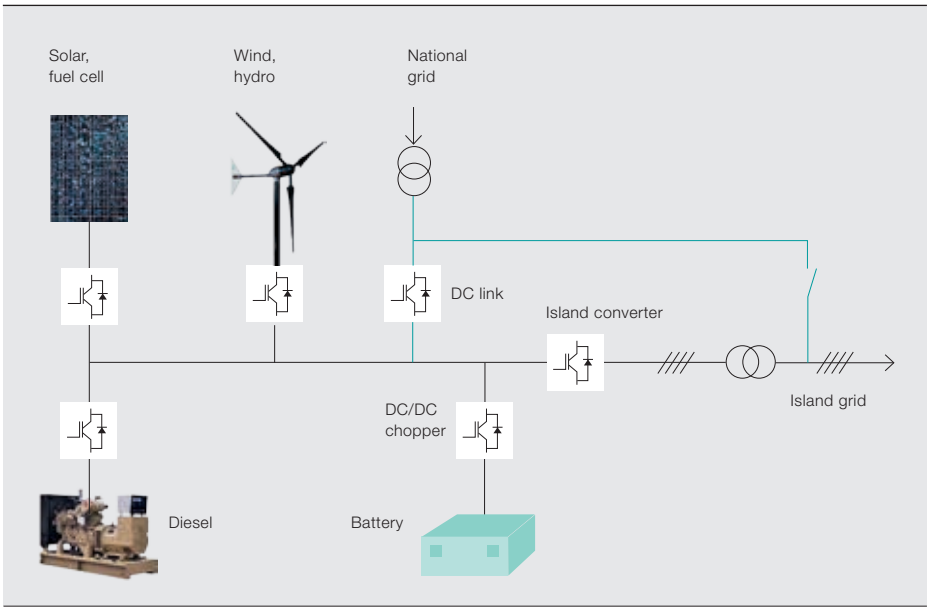
One main criterion in judging the performance quality of the island converter is the fault current capability. Now that the converter is part of the islanded grid, it has to provide the fault current required to clear the fault and protect the equipment and personnel.

The island converter can run in parallel with other island converters and in parallel with the national grid. The number of parallel converters is not limited – from the technical point of view any number can be connected to supply a common island grid. However, at some point, using a rotating generator will be more beneficial than implementing a huge number of parallel converters.

Other applications built on DTC modulation

The control of the two applications presented above is founded on the ACS800 software platform. In each case, the direct torque control (DTC) modulation principle is used. DTC is an AC motor control method developed by ABB in

3 Configurable power provision in smart grid application



Power electronic converters can be used to build an intelligent and highly reliable island grid.

which all switch changes, for every control cycle, are based directly on the electromagnetic state of the motor; there is no separate voltage- and frequency-controlled pulse-width modulator. The first major successful commercial DTC products were developed by ABB in the 1980s for traction applications. DTC relies heavily on digital signal processing and dedicated electronics. The use of DTC allows special converter applications based on ACS800 motor control to be developed. This development work is carried out by a dedicated ABB software team.

Benefits of scale

All the applications mentioned profit from commonality. Each application has its specific software, but the IGBT converter module hardware remains the same. This brings benefits of scale to prices, volumes, reliability, spare parts and global aftersales service.

Size

The modular construction of the ACS800 product series is extremely beneficial and flexible when building complicated converter applications. The smallest reasonable module size in PQ and islanding applications is 150 kVA in an R7i frame and the largest module size is 500 kVA. By paralleling these larger modules, a single converter with a rated power of about 5 MVA can be realized.

The largest PQ converter so far is a 4.5 MVA liquid-cooled ACS800 multidrive supply unit in a test field in Helsinki. It supplies active power to large AC drives. In addition, it compensates the reactive power of the entire test field and filters out the most significant characteristic harmonic currents. When running high-power six-pulse rectifiers in the test field, a reduction of 45 percent in MV current was measured when the PQ converter was enabled. This reduction in reactive power results directly in a savings of several thousand euros per month in the electricity bill.

The biggest island units in operation so far are two (for redundancy) 2.2 MVA liquid-cooled converters operating in parallel on a new Norwegian ship. The ship also has two 0.9 MVA liquid-cooled island converters. These converters are part of multidrive systems.

The applications described above show how ACS800 hardware, coupled with special software, can save energy, increase power quality and provide reliable power in the event of disturbances. Other applications are just a matter of developing the appropriate software. Given the capabilities of the technology, the number and variety of new applications is expected to increase.

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Hot spot

A new infrared sensor measures temperature in generator circuit breakers

STEPHAN WILDERMUTH, ULF AHREND, MORITZ HOCHLEHNERT, MARCO ULRICH – The generator circuit breaker (GCB) is of great importance for the undisturbed operation of a modern power plant. It typically sits between a generator and its transformer to protect this equipment from damage, while handling very high currents – typically tens of kA. With such high currents, even a small increase of resistance in the current-carrying path will lead to a large temperature increase in the breaker – and this can have very dramatic effects. Temperature supervision is, therefore, essential. This, however, can be a very challenging task in the high-voltage (HV) environment so ABB embarked on a development program to produce a new temperature sensor system for GCBs.

1 Pumped storage power plant application with HECPS-3S

GCBs are used, for example, in fossil-fueled, nuclear, gas-turbine, combined-cycle, hydropower and pumped-storage power plants. They have a tough job. During normal operation of the power plant, the GCB has to carry the full nominal current of the generator, which can easily reach 23 kA without bus cooling or over 30 kA with active cooling – all at potentials of up to 32 kV ➔ 1.

At such high currents, even a slight increase of electrical resistance in the current-carrying path leads to a large temperature increase. Increased resistance can arise from connection misalignment, dust inside the GCB or damaged contact surfaces. The consequent heating can lead to damage to internal silver-plated contact areas, such as the bus duct connection zones, the line disconnector and the contact system of the interrupting chamber. Heat removal from the main conductor is partly done by radiation, so paint with high emissivity is usually applied to the conductor – but this cannot cope with significantly elevated temperatures (normal operating temperatures are in the range of 70 to 90°C).

Excess temperature can lead to loss of interrupting capability or even provoke a flashover if components start to melt.

GMS600

ABB's GMS600 is a GCB monitoring system that indicates the need for maintenance and provides early warning to avoid unexpected downtime ➔ 2. The GMS600 calculates remaining time-to-overhaul based on cumulative current interruptions, total number of mechanical operations, time from last overhaul, circuit breaker main drive supervision, SF_6 density and so on. One aspect missing from its repertoire was temperature supervision. This was because no commercially available temperature sensing system fulfilled all the technical, commercial and functional requirements for an accurate and reliable temperature monitoring of GCBs during operation.

This lack of a commercial system is not surprising as the temperature supervision of HV components can be challenging. For example, the temperature sensor has to survive severe electromagnetic conditions and can also be exposed to steep temperature gradients caused by, eg, desert climate.

A new temperature sensor system had to be developed.

Sensor development and design

A detailed technical analysis determined that a temperature measurement scheme based on the detection of infrared radiation (IR) was the best approach. The goal then was to take a commercially available IR sensor element and package it to operate reliably in the demanding GCB environment.

> At such high currents, even a slight increase of electrical resistance in the current-carrying path leads to a large temperature increase.

The central component of the IR temperature sensor is the IR detector element itself. Non-cooled Si-based thermopile detectors were chosen due to their good cost/performance ratio. The only way to ensure proper performance of the sensor under the severe conditions encountered in a GCB – spatial and temporal temperature gradients and high electromagnetic

Title picture
Accurate and reliable monitoring of the temperature in GCBs (ABB's HEC8 is shown) is essential as the slightest increase in resistance can lead to a rapid temperature rise because of the very high currents flowing. How can temperature be monitored in such a challenging environment?

The goal was to take a commercially available IR sensor element and engineer it to operate reliably in the demanding GCB environment.

2 Central condition monitoring device GMS600

fields with fast transients – was to appropriately package the IR detector and the electronics.

In addition to the detector ASIC, additional electronics were included to convert the digital SMBus output signal to Modbus. These electronics, too, must withstand the severe EMI (electromagnetic interference) environment of a GCB.

The housing of the IR sensor element was surrounded by a material with high thermal conductivity.

The sensor package, therefore, needs to fulfill three major objectives:
- Suppression of large spatial temperature gradients at the IR sensor element
- Suppression of large temporal temperature gradients at the IR sensor element
- Suppression of EMI

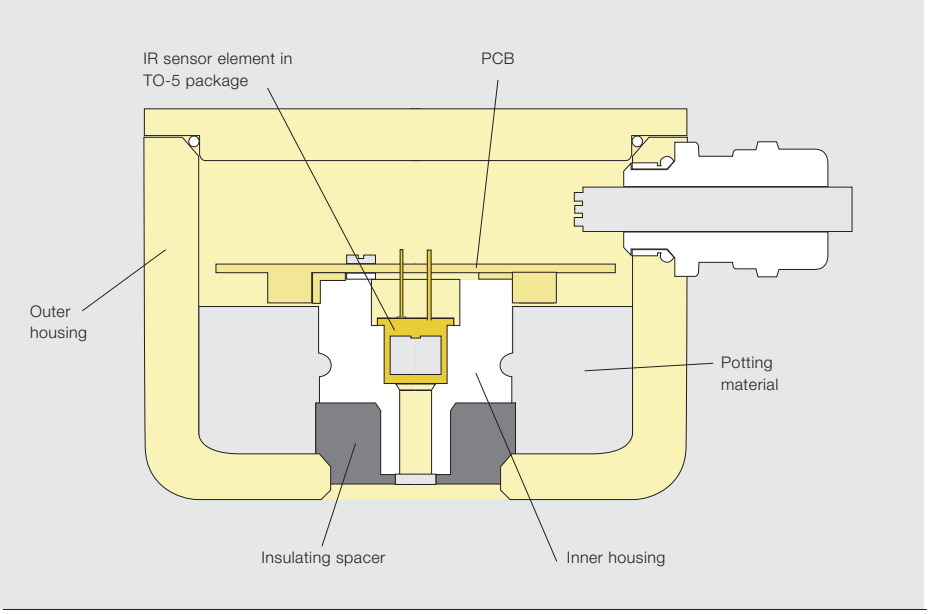
In order to fulfill the first objective, the housing of the IR sensor element was surrounded by a material with high thermal conductivity → 3. This ensures that temperature gradients immediately equilibrate and the thermal field around the sensor remains homogeneous.

The second objective can be satisfied by choosing a design that leads to a large thermal time constant (in the range of several minutes). The time constant of the sensor package can be increased by giving the sensor and aperture a large thermal mass, and by reducing thermal conductivity around the sensor to delay heat ingress to the sensor.

The package is, therefore, a two-part-housing concept where the inner and outer parts are thermally weakly coupled → 3. This approach inherently satisfies the dielectric and EMI requirements, too: The outer housing acts as a Faraday cage and the thermal insulation acts as an electrical insulator as well as a heat barrier. As an additional EMI countermeasure, the outer housing is grounded through the GCB enclosure and the inner housing is connected to a local ground potential.

Package dimensioning was defined by transient thermal finite element method (FEM) simulations of a simplified thermal model → 4. The design goal was to achieve a thermal time constant greater than 10 minutes. This duration was predicted by the simulation and verified by experimental tests later on.

3 Schematic of the cross section of the sensor package showing the main functional components



The outer housing acts as a Faraday cage and the thermal insulation acts as an electrical screen as well as a heat barrier.

Prototyping and testing

To check the thermal design and to verify good thermal coupling of the IR sensor element to its surroundings, temperature shock experiments were performed. The IR temperature sensor was exposed to an ambient temperature change of 25°C to 70°C. The rise time of 5°C/min was limited by the heating power of the climate chamber used. For the duration of the experiment the IR temperature sensor stared at a black-body radiator held at a constant 80°C. Very good sensor performance (error less than 2°C) was found if the thermal coupling to the inner housing was guaranteed by a thermal grease or adhesive.

To verify the performance of the IR temperature sensor, 21 sensor prototypes were built and subject to different environmental scenarios simulated by the climate chamber. Sensor response to a black-body radiator temperature range of 30°C to 120°C at a constant ambient (sensor) temperature of 25°C was tested. The sensor response displayed a linear behavior. The linearity error remained below 3°C over the entire object temperature range. The variations (standard deviation) between the individual prototypes were found to be 0.8°C and 1.2°C at an object temperature of 75°C and 120°C, respectively.

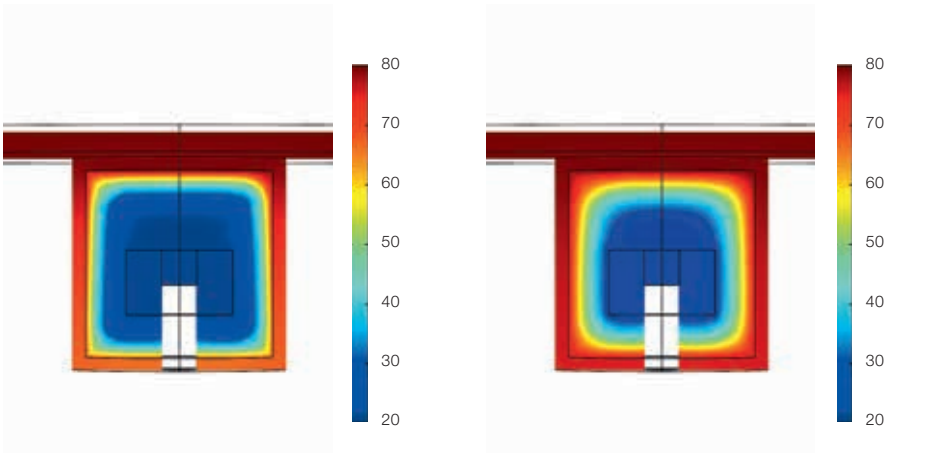
Large temporal temperature gradients at the IR sensor element can be avoided by choosing a design that leads to a thermal time constant of several minutes.

A very important task for the IR temperature monitoring system is the detection of GCB overloading, when the temperature of the main conductor can approach 120°C. This scenario was simulated by changing the object temperature range from 80°C to 120°C → 5. The IR sensor accurately captured this temperature change and the measurement deviation stayed well within the required accuracy interval of ± 3°C.

To assess the influence of changes in ambient temperature, the IR temperature sensors were exposed to three consecutive temperature cycles from −5°C to 60°C at a rate of 0.1°C/min. This rate of temperature change was chosen to simulate a typical day/night scenario.

The only way to ensure proper performance of the sensor under the severe conditions encountered in a GCB was to appropriately package the IR detector, the enclosure and the electronics.

4 FEM simulation of the sensor package heating. This gives a first estimate of the thermal time constant of the whole sensor package and was used to define the package dimensions



4a After 73 s

4b After 200 s

4c After 400 s

4d After 600 s

Again, typical sensor measurement error remained below 3°C. Furthermore, in humidity tests, the sensor measurement error was less than 2.5°C up to 90 percent relative humidity, at an ambient temperature of 60°C.

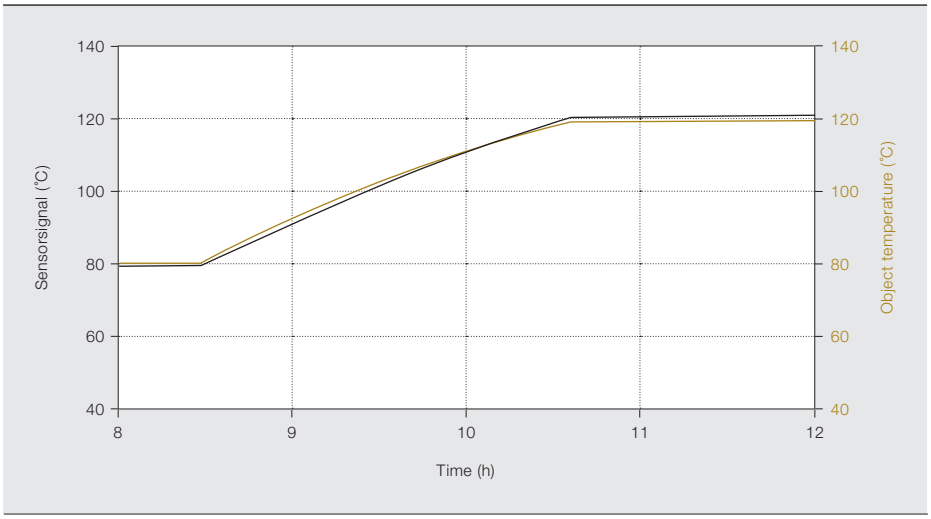
The IR temperature sensors were also tested for other disruptive factors encountered in a GCB environment. This included extensive vibration testing to simulate mechanical shock experienced during GCB switching operations. Electromagnetic immunity was tested according to IEC 61000-4 and IEC 61000-6, addressing immunity to RF electromagnetic fields and electrostatic discharges, as well as electrical fast transient tests (severity level 3 required). All tests were successfully passed and the sensor system thus qualified for operation in a GCB.

Productization phase

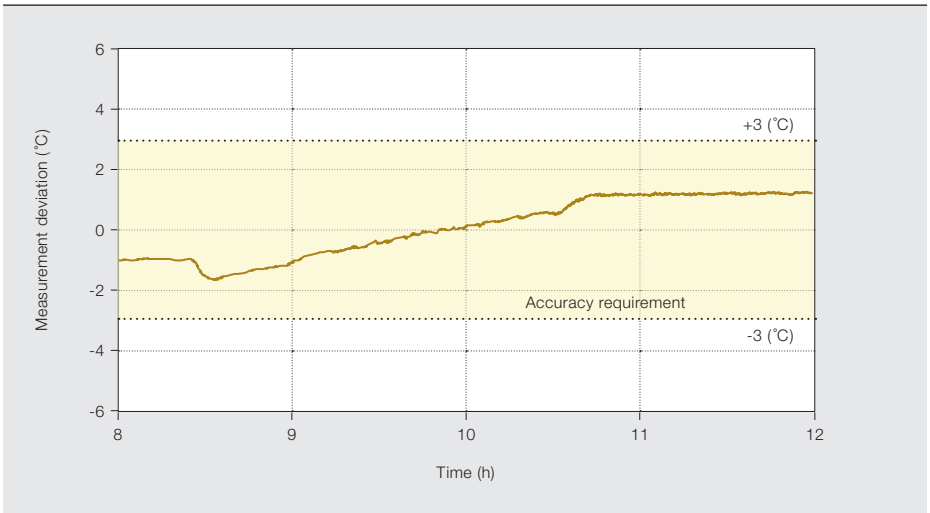
The involvement of a potential manufacturer early on in the project resulted in a very mature technology demonstrator. Only a few changes were necessary for full productization.

Productization was done in parallel to the adaptation work on the sensor itself. This covered the sensor assembly, cable harness design, mechanical integration of the sensors into the GCB enclosure, routing of cables, and a GMS600 monitoring software update to log, store and present the temperature data to the customer for nine sensors (three per phase). The supply chain was put in place in cooperation with the manufacturer, who also preassembles sensors and cables on a mounting rack to speed installation in the GCB.

5 Climate chamber simulation of GCB overheating: IR temperature sensor response



5a IR temperature sensor signal at an object temperature from 80°C to 120°C over several hours



5b Measurement deviation stays well within the required accuracy interval of ± 3°C during the entire temperature ramp.

To check the thermal design and to verify good thermal coupling of the IR sensor element to its surroundings, temperature shock experiments were performed.

Extended service

Cost-efficiency can be significantly improved by intelligent service approaches, such as predictive maintenance. However, efficient, adaptive and sustainable predictive maintenance and equipment life strategies are highly dependent on meaningful sensor signals from the field.

The robust and cost-effective temperature sensor system described here enables reliable temperature monitoring of GCBs during operation. In combination with other sensor information (eg, vibration or contact ablation) a clear picture of a device's health condition can be derived and predictive maintenance strategies formulated. This is especially important for GCBs where overheating of the main conductor can lead to the power plant shutting down, which can result in high cost and potentially disastrous equipment damage.

Access to this kind of condition data also enables new service concepts and business models to be created, and provides valuable feedback for the design of new devices. Finally, statistical analysis of data from an entire fleet of devices can reveal information unobtainable from a single device. This opens up new opportunities and value propositions for ABB to offer to end customers through its service portfolio.

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At a higher level

A medium-voltage-level UPS for complete power protection

SOPHIE BENSON-WARNER – ABB has developed a range of medium-voltage (MV) uninterruptible power supplies (UPSs) with ratings up to 6 MVA. Implementing a UPS at the MV level has many practical advantages and is an approach being adopted by customers in industry and in large data centers who have sensitive or critical loads. The PCS100 MV UPS range complements existing ABB low-voltage (LV) UPS and power conditioning products.

Title picture
Moving the UPS up to the MV level has many advantages for industrial users and data centers.

1 The PCS100 MV UPS is suitable for protecting sensitive loads.

Our modern society now relies on the ready availability of a vast amount of data. Almost every organization – health authorities, banks, government departments, retail outlets, corporations and so on – requires the safe storage of enormous amounts of information. Further, much industrial and domestic activity has become fully dependent on a wide range of electrical devices. An added complication is the arrival on the power grid of an ever-increasing number of renewable generators that has led to an increase in power-quality-related problems like spikes, swells, sags, noise and harmonics that pose a risk to all power users.

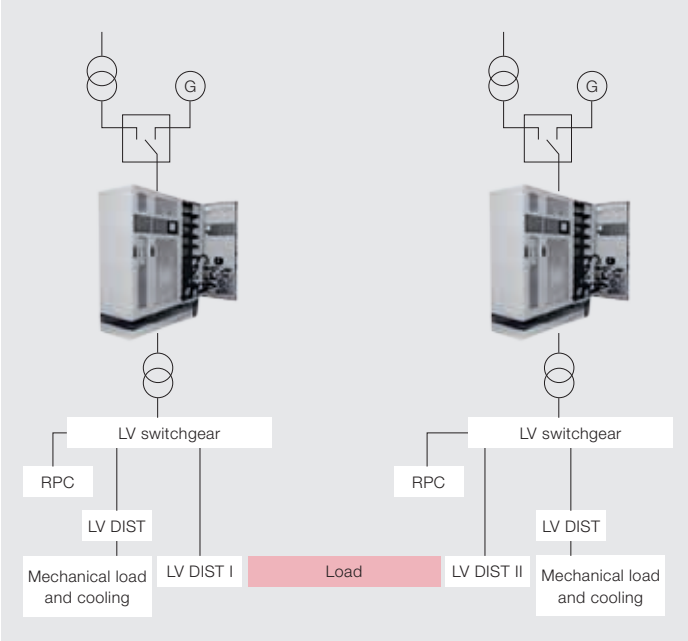
The dependence on a rock-solid supply of good-quality power has driven the massive growth in the UPS and power conditioner business in recent years. Traditionally, these devices are fitted at the LV level, but this can often pose a challenge if the space available is limited. Also, where many devices are to be protected, the sheer number of UPSs needed can present problems in terms of management, supervision, maintenance and availability. The solution is to install the UPS at the MV level.

When installed at MV levels, the UPS can be put in less-crowded spaces away from the target devices – in MV electrical rooms or plant substations, for instance – thus freeing up space for more important infrastructure, such as servers or manufacturing tools.

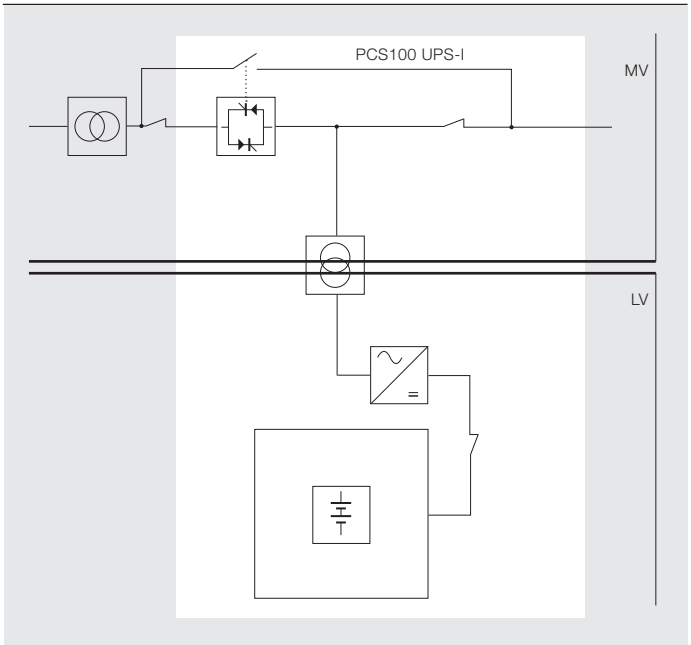
ABB's PCS100 MV UPS range is aimed squarely at this market segment. It has been designed specifically to provide clean, reliable and efficient power, and lower costs for customers in industry and in large data centers who have sensitive or critical loads.

When installed at MV levels, the UPS can be put in less-crowded spaces away from the target devices – in MV electrical rooms or plant substations, for instance.

2 An MV UPS can be configured to protect an entire data center load or just the mechanical loads.



3 Single-conversion topology is a natural choice for MV. Power electronics and power storage can remain at LV with transformer coupling to MV.



The PCS100 MV UPS can be installed to protect the complete supply or just selected sensitive loads ➔ 1. In a data center this could include the mechanical loads ➔ 2. Installing the UPS protection at the MV level provides the most energy efficient configuration as the lower currents at this voltage result in lower losses.

The first release is rated up to 6.6 kV and 6 MVA with even larger 15 kV class products to follow (including 11 kV and 13.2 kV options), rated at even higher MVA.

PCS100 MV UPS technology

The single-conversion topology used is a natural choice for MV as losses are extremely small, meaning efficiencies well in excess of 99.5 percent can be achieved. It also allows a system design where the power converter and energy storage can remain at LV, with a transformer coupling these to MV ➔ 3. Also at the MV level is a thyristor-based utility disconnect switch which prevents backfeed into the grid in the event of a power loss or voltage sag.

Lower cost

Up-front cost is always important in equipment selection, but the total cost of ownership is usually the most important cost criterion for the customer. The unparalleled efficiency of the PCS100 MV UPS, its low maintenance costs and small system footprint minimize ownership costs. The fact that the energy storage and converter is at the LV level also greatly simplifies maintenance and reduces system cost. Finally, the PCS100 MV UPS has many retrofit possibilities that allow custom designs that suit applications in plants that are currently unprotected or where traditional rotary UPS solutions require replacement.

Storage options

Because the energy storage is kept at LV levels, a wide range of energy storage options is available. The most common are ultracapacitors, lithium-ion batteries and high-discharge sealed lead-acid batteries. It is expected that ultracapacitors will be widely used in industrial applications due to their long life and compact size. For longer-autonomy applications, lithium-ion batteries similar to those used in electric cars offer reduced footprint and increased life when compared with the lowest-cost lead-acid solutions. Lithium-ion batteries have excellent cycle life characteristics and this opens up opportunities for smart grid support features, such as load shedding, to be added.

The PCS100 MV UPS can be installed to protect the complete supply or just selected sensitive loads.

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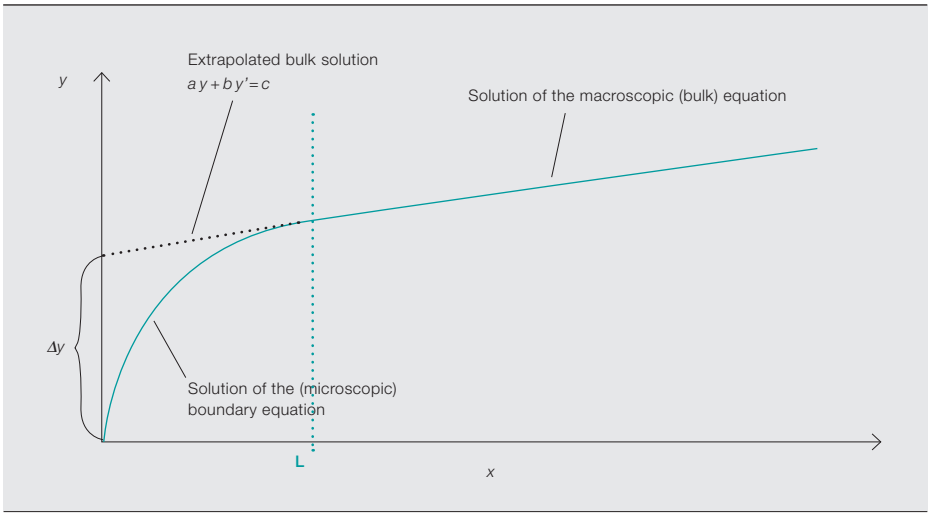
Boundaries of knowledge

Knowledge of boundary conditions is crucial for reliable simulations

KAI HENCKEN, THOMAS CHRISTEN – Partial differential equations (PDEs) are the basic language with which physicists describe many natural phenomena, such as electric and magnetic fields, acoustics, fluid flow, and heat conduction. The PDEs that describe the physics inside a spatial domain of interest – so-called bulk equations – are the key elements in numerical simulations of ABB products [1]. However, at the boundaries of many systems the variety of underlying physical processes that need to be taken into account is far richer than in the bulk. In addition, boundaries often govern the result of a simulation even though they only occupy a small part of the whole system. Hence, in obtaining meaningful numerical simulations, appropriate boundary conditions can play a decisive role. Describing these mathematically is, in general, not an easy task and requires a deep insight into the underlying physics.

1 Derivation of boundary conditions for a macroscopic equation from the underlying microscopic physics



PDEs describe the behavior of physical properties or quantities in space and time. Typical examples are the heat equation for temperature, the Laplace equation for electric potential, and the fluid dynamics equations for mass, momentum and energy flow.

The occurrence of (mathematical) spatial derivatives in these PDEs is associated with a coupling of a given point in space with its surroundings, often due to a transport phenomenon. In order to obtain well-defined, ie, unique, solutions of the PDEs, boundary conditions must be specified. This is similar to the requirement for an initial condition in order to solve for a time-dependent process – the conditions at the starting time of a simulation can be interpreted as a boundary condition for the time axis, as an analogy. The general mathematical form of specific boundary conditions mainly depends on two structural properties of the bulk equations.

The first property is the order of the PDE, which indicates the highest spatial derivative that occurs in the bulk equation. For instance, the heat equation is of order two, as a derivative of the form $\partial^2 T/\partial x^2$ occurs. The boundary conditions will, in general, be a relation between the physical quantities and their (spatial) derivatives with an order smaller by one than the order of the PDE itself, because higher order derivatives can be eliminated with the help of the bulk PDE. For instance, in the steady-state heat equation, $\partial^2 T/\partial x^2 = 0$, the boundary condition might, in principle, contain arbitrary spatial derivatives, not only T itself and its derivative. But terms of the form "$\partial^2 T/\partial x^2$" or higher can be eliminated using $\partial^2 T/\partial x^2 = 0$.

The second property concerns how information propagates inside the bulk, ie, how a disturbance or change of a physical quantity at one point influences its value at a distance at the same or a later time.

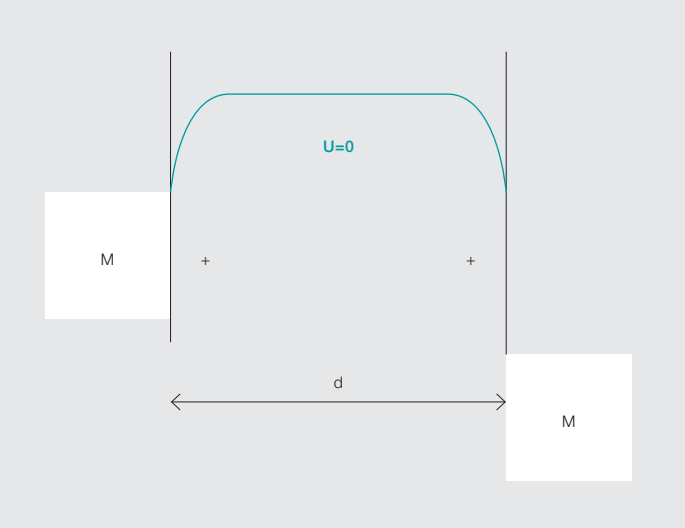
The simplest example is a PDE of order zero. Spatial derivatives and propagation are then absent and boundary conditions are superfluous. The equation is, in this case, a (distributed) system of ordinary differential equations (ODEs) rather than a PDE. A physical example of this is the electric polarization induced in a dielectric medium, which can be described by a relaxation process of the local polarization density.

There are other cases where a boundary condition is unnecessary, even if spatial derivatives occur. For instance, the state of a supersonic fluid at an outlet is completely determined by the information coming from the bulk. Because the fluid flows faster than the speed of sound, which is the information velocity in this case, no information can flow backward from the boundary into the bulk. Hence, this boundary will not affect the state in the bulk.

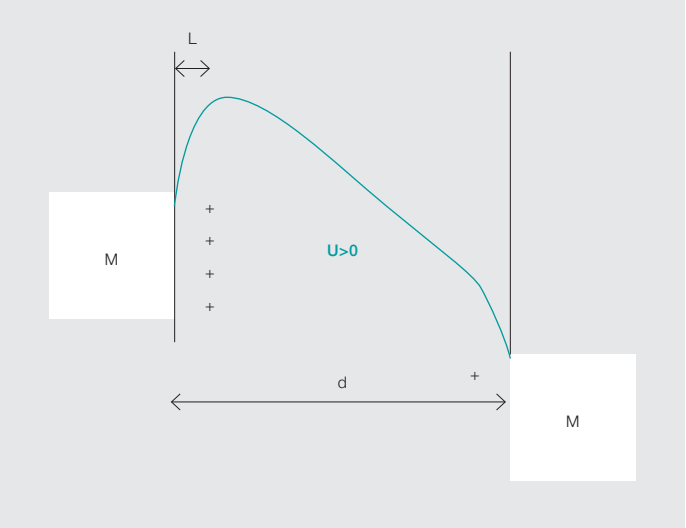
Boundary conditions are usually necessary and are classified according to the propagation behavior of the PDEs – diffusive, instantaneous, convective or wavelike. For example, instantaneous propagation corresponds to steady-state solutions, where one implicitly assumes that the propagation and, therefore, the equilibration, in the system is much faster than the timescale considered. An example is the formation of an electric field (eg, in a vacuum), which is usually described by the instantaneous Laplace equation.

For meaningful numerical simulations, bulk models have to be complemented with appropriate boundary conditions.

Title picture
Products contain many internal boundaries, surfaces and interfaces that strongly determine their performance and which must be described in simulations by boundary conditions.



2a Insulator without intrinsic, but with injected, charge carriers (here positive holes) from the two attached electrode contacts. (Blue: equilibrium potential.)



2b Application of a voltage tilts the energy potential seen by the carriers, leading to a maximum near the injecting electrode.

The boundary conditions have to be formulated in a way that makes the model well-posed, ie, a physically reasonable solution exists.

Transients can in practice often be disregarded due to the fact that the electric field travels with the speed of light.

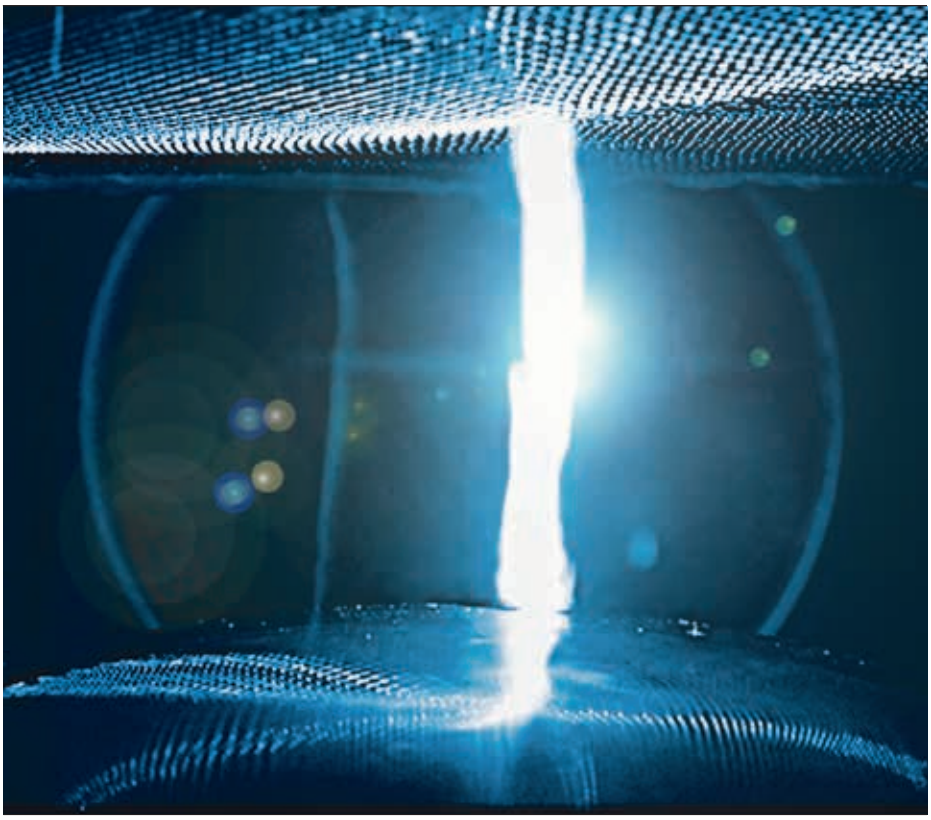
The boundary conditions have to be formulated in a way that makes the model well-posed – ie, a physically reasonable solution exists. This can impose restrictions on the number and types of conditions that are needed at each boundary.

Boundary condition physics goes beyond bulk physics

As mentioned, the bulk equations constrain and prescribe the functional form of the boundary conditions. However, the values of the coefficients or parameters occurring in them are still free and need to be determined by the underlying physics. This can be a sophisticated task, as boundary conditions need a more detailed view into the physical system than the bulk PDEs. Bulk PDEs are derived by averaging quantities, like thermal energy, over small volume elements in which these quantities are considered homogenous. At boundaries, the properties change abruptly, making consideration on a shorter, eg, microscopic, scale necessary. As a consequence, boundary condition modeling must take physics at a higher level of detail and greater variety of phenomena than the bulk equation into account.

An important example of this is represented by bulk equations for a gas under the assumption of local thermodynamic equilibrium, where the temperature is well-defined and the velocities of the particles follow the Maxwell distribution. When approaching the boundary, this velocity distribution deviates from the one in the bulk due to surface effects and thermodynamic equilibrium is no longer a given → 1. In other words, the macroscopic equations for the physical quantity $y(x, t)$ along the x-axis of → 1 are valid for distances larger than a certain microscopic length L, but not below it. The magnitude of this boundary region is assumed to be much smaller than the scale that is resolved in the numerical simulation. The extrapolation of the bulk solution to the boundary does not necessarily coincide with the microscopic solution. However, the boundary condition has to fulfill the mathematical relation set by the bulk equation.

3 An electric arc burning between two electrodes. The arc root forms an interesting and complex boundary.



In this case it is given by a general relation of the form

$$ay+by'=c$$

The coefficients a, b and c must be obtained by enforcing a smooth transition from the microscopic to the macroscopic solution. For instance, even if the fundamental microscopic physics calls for $y=0$ at the boundary $(x=0)$, the macroscopic boundary condition may exhibit a discontinuity due to the physics in the microscopic boundary layer. An important example is a slip boundary condition for the (macroscopic) gas flow velocity in a pipe, where one assumes a finite velocity all the way to the wall, although microscopically, ie, in a very thin viscous boundary layer, it rapidly decreases to zero at the wall.

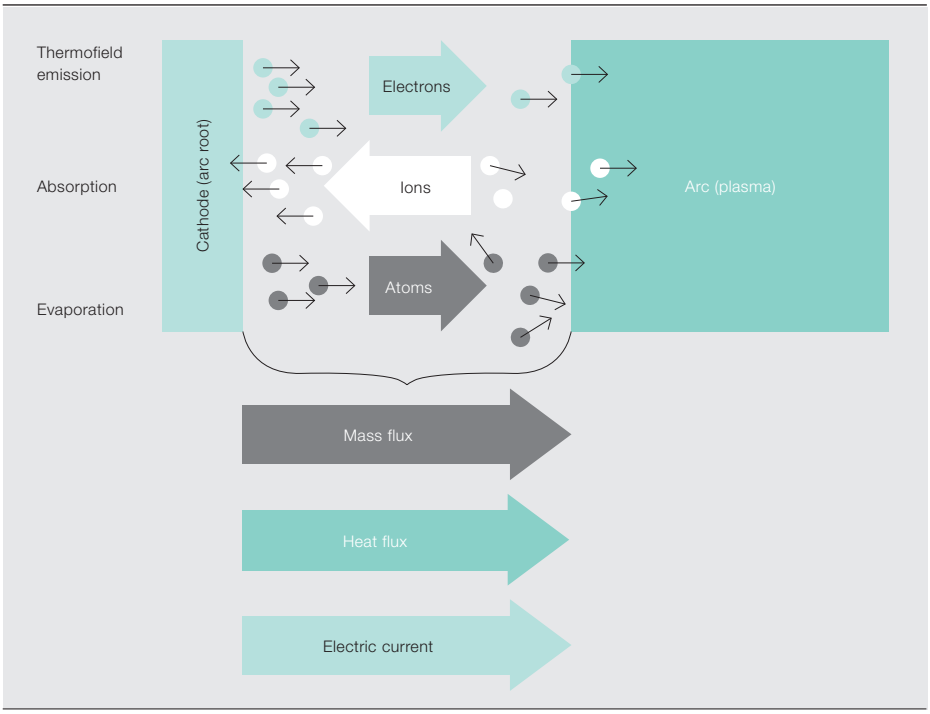
DC conduction in insulators

In AC cables, the 50 Hz field distribution is usually calculated by solving a Laplace equation for the electric potential in the dielectric materials, with appropriate boundary conditions on the conductive parts. The relevant material property is the dielectric permittivity and any accumulation of charges within the dielectric materials can be neglected.

> The underlying physics that needs to be taken into account at boundaries is much richer than for bulk equations.

Field calculations in DC insulation, however, are considerably more complex because space charges can build up inside the material. By this, sometimes very slow, process, the field distribution may change significantly over time. An illustrative example of the coupled interaction of the boundary with the bulk is the formation of a space-charge-limited current (SCLC): Consider a material that is initially bare of any charge carriers and with a metal contact on each side → 2. Even without an applied voltage, charge carriers (positive holes, say, for simplicity) will diffuse from the electrodes into the insulator.

4 A number of physical phenomena occur in an arc root – only the microscopic view shows the interdependency between them.



Charge injection from electrodes can be of great relevance when designing HVDC cable and accessories.

There, they create a thin charge accumulation layer that leads to an increased, almost flat, potential distribution in the interior of the insulator. The electric field, which is essentially the negative slope of the potential, is thus practically zero everywhere between the plates, except near the contacts → 2a. A high voltage applied across the electrodes induces a strong tilt of the potential that leads to a potential maximum near one of the electrodes → 2b.

Typically, this distance is too small to be resolved in the macroscopic simulation and is excluded. But this maximum has important consequences. The electric field is zero at the maximum, as it is, by definition, the slope of the potential. This location is called the "virtual electrode" and electrodes that exhibit this property of vanishing field under these conditions are named "ohmic electrodes." Because the electric current – which is proportional to the product of the electric field, the charge carrier density and their mobility – remains finite, a vanishing electric field together with a nonzero current implies that the charge carrier density diverges (becomes infinite) at the virtual electrode. In reality, the density remains, of course, finite due to the action of diffusion, which was, in this simple picture, neglected. The electrode injects a large number of charge carriers, leading to such a large charge density at the contact that the electric field is suppressed. This can lead to a field enhancement at another place or after polarity reversal.

Charge injection and accumulation is of great relevance when designing HVDC insulation devices. A main consequence of it is that the electric field distribution is then not only determined by a bulk conductivity, but is also influenced by contacts and the boundary between them, which requires special measures to make HVDC insulation robust [2].

Arc roots in vacuum circuit breakers

In vacuum circuit breakers (VCBs), the interruption of currents occurs via the formation and extinction of an electric arc [3] → 3. First of all, as the bulk mate-

Circuit breakers rely strongly on boundary effects – for example, metal vaporization in vacuum breakers and nozzle ablation in gas circuit breakers.

rial here is vacuum, the relevance of appropriate boundary conditions is obvious because the metal plasma in the VCB completely originates from the electrodes. Secondly, the example presents a complex multiphysics boundary problem, since a number of different physical phenomena are involved that can be treated independently in the bulk, but are connected at the lower level.

Arc roots are the areas where the arc connects to the metal electrodes. An electric layer is formed at an arc root. This non-neutral sheath leads to a voltage between the bulk of the plasma and the electrode – ie, the electrode voltage drop, similar to what is shown in ➔ 2a. This voltage drop leads to a strong electric field at the surface. This is needed to draw a large electric current from the metal to the plasma by making electrons leave the cathode or enter the anode and by making ions move to the surface ➔ 4. This ion movement and recombination is the dominant heating mechanism for the metal. The electrode surface in the arc root becomes so hot that metal evaporates. The vacuum arc is actually a metal vapor arc that feeds itself purely from the material emitted from the arc roots. The balance of the surface heating from the plasma and the cooling by metal evaporation determines the electrode temperature and, by this, the performance of the breaker.

Each of these processes is complex in itself, but, because the same particles (electrons, ions and atoms) are the carriers of different properties (mass, heat and electric current), the boundary conditions are interrelated and this has to be taken into account if a consistent simulation is to be obtained.

Another example of the relevance of boundary effects is found in arc-radiation-induced material ablation in gas circuit breakers, which is relevant for the pressure buildup needed in the switching process [1].

Further examples are to be found in sensors, oil-insulated HV equipment and so on.

Reliable simulation

For meaningful numerical simulations, bulk models have to be complemented with appropriate boundary conditions. Boundaries often have a substantial effect on the result even though they only occupy a small part of the whole system. Furthermore, the variety of underlying physical processes that need to be taken into account in boundaries is much richer than in the bulk, whose equations often follow from simplifying conservation laws.

It is wise, when validating simulation results, to scrutinize the boundary conditions used, for two reasons: First, due to their large effect, it is sometimes easy to produce the desired results by tuning boundary condition parameters. Second, the physics behind boundary conditions is often very complex and can be treacherous. Choosing a good boundary condition is not an easy task and requires a deep insight into the underlying physics, but the effort pays off by delivering much more reliable simulation results. Last but not least, an understanding of the governing boundary physics can be an important source of technical innovation.

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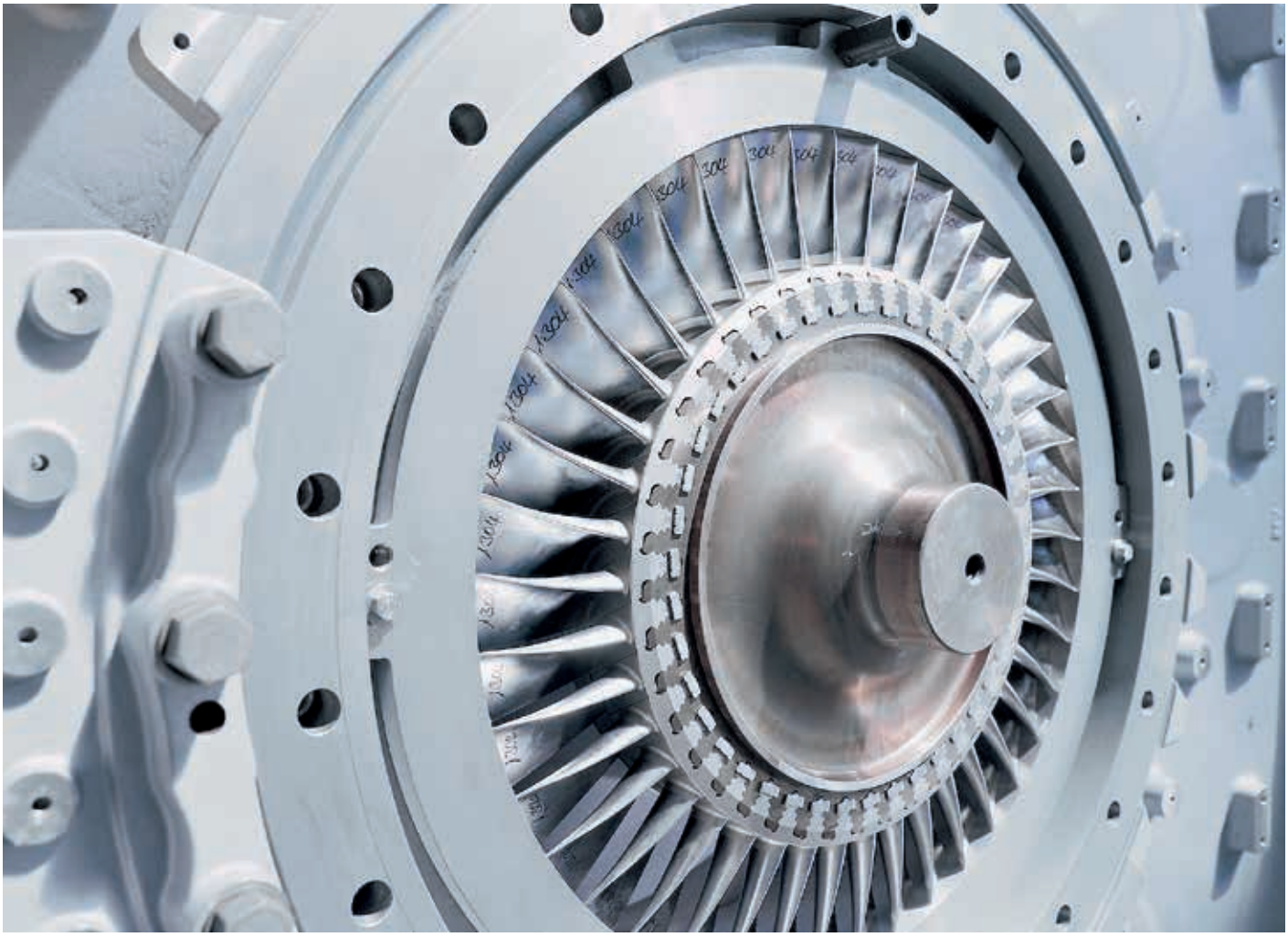
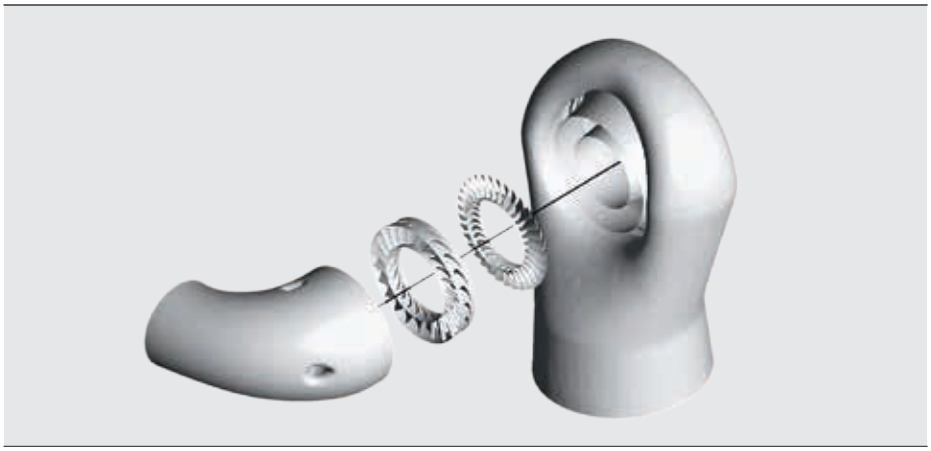


Pushing the limits

Turbine simulation for next-generation turbochargers

KWOK-KAI SO, BENT PHILLIPSEN, MAGNUS FISCHER – Computational fluid dynamics (CFD) has matured and is now an indispensable tool for turbomachinery design and development. In particular, aerodynamic analysis and optimization of axisymmetric rotors and stators based on CFD has become a standard procedure in the development process. Measurements of turbocharger turbines on a test rig have indicated that distortion of the symmetric flow at the inlet and the outlet of the turbine can have a significant influence on turbine performance. Based on CFD simulations of the complete turbocharger turbine from inlet flange to outlet flange, this influence was confirmed and a turbine geometry less sensitive to the distortions was found. These simulations have pushed the limits of the application of CFD to turbine design.

1 Computational model of the turbine stage. Left to right: intake manifold, nozzle ring, rotor and exhaust manifold.



2 Turbocharging multiplies power

ABB is at the helm of the global industry in the manufacture and maintenance of turbochargers for 500 kW to 80+ MW diesel and gas engines. ABB's technology and innovation enables customers' equipment to perform better and produce fewer emissions, even in the toughest environments. Approximately 200,000 ABB turbochargers are in operation across the globe in ships, power stations, gensets, diesel locomotives and large, off-highway vehicles. ABB has over 100 Service Stations in more than 50 countries and guarantees original parts and original service.

A typical turbocharger consists of two main systems ➔ 3: the turbine stage (orange section in figure) that recovers the power from the diesel engine exhaust gas; and the compressor stage (blue section) that boosts compressed air to the diesel engine. With a turbocharger, a diesel engine delivers four times the output power a naturally aspirated engine would. In other words, the turbocharger multiplies engine power. In addition, turbocharging technology is the main driver for the reduction of fuel costs and NO_x emission in diesel and gas engines.

A turbocharger for a high-power application typically has an axial turbine stage that includes a nozzle ring and a rotor. The turbocharger's intake manifold directs the gas flow into the axial turbine stage upstream of the nozzle ring. The gas expands in the turbine stage and drives the rotor. Downstream from the rotor, the exhaust manifold functions as a diffusor – an element critical to the performance of the turbine stage ➔ 1–2. The gas flow through the turbocharger components must be engineered to ensure maximum turbine performance and, in this regard, CFD plays a critical role in the development of turbochargers.

Challenges in turbine simulation

Conventional CFD simulation of an axial turbine stage is usually performed on two components, namely the nozzle ring and the rotor. Typically, only the flow inside one segment of the nozzle ring and the rotor is simulated – the simplification of a periodic axisymmetric flow condition is assumed. Traditionally, the simulation and design of the intake and exhaust manifolds are carried out in a separate, standalone process. The advantage of this sequential design approach is the relatively low computational demand of flow simulation for one channel of the nozzle ring and the rotor. Also, the approach works well for regular axial inflow and outflow conditions. However, the simulation of the manifolds alone, without the turbine stage, is not a complete simulation as the interaction between the turbine stage and the manifolds is not taken into account.

> The flow through the components must be engineered to ensure maximum turbine performance and, in this regard, CFD plays a critical role.

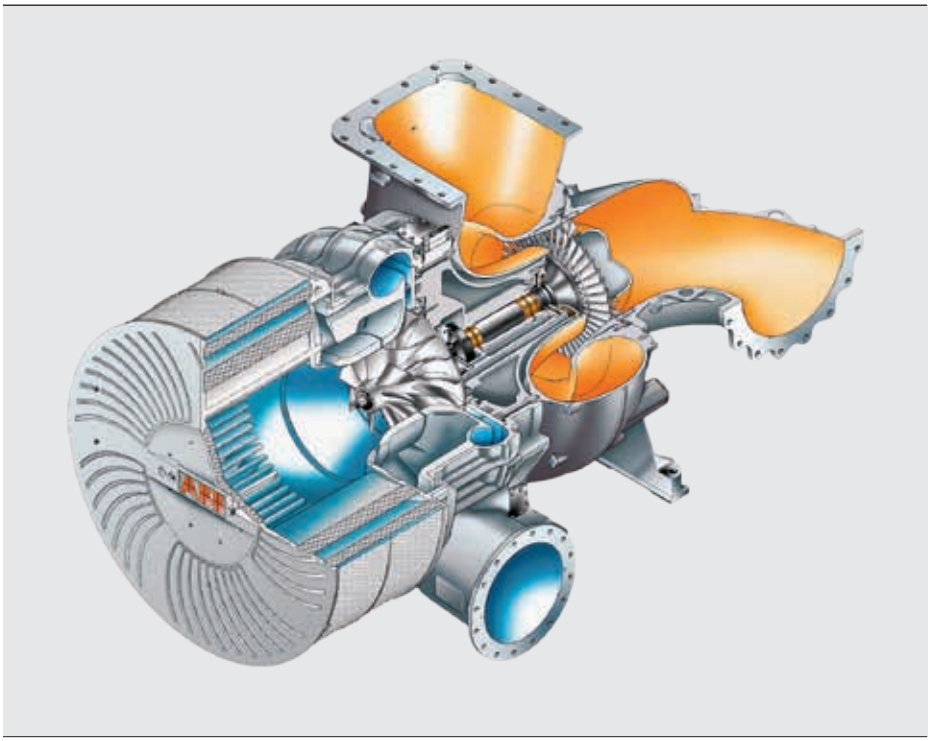
The challenge in turbine-stage simulation arises when the intake manifold and the exhaust manifold exhibit severe turns and radial bends, due to spatial requirements. In this case, the assumption that the inflow and outflow paths are axially symmetric no longer holds. These flow deviations can have a significant effect on the diffusor and turbine performance as undesired flow recirculation and separation can occur in the diffusor region and result in a drop of turbine efficiency. Up until now, finding a suitable diffusor involved several design iterations with extensive test runs.

In order to investigate the flow of the axial turbine stage with various intake or exhaust manifolds without having to test these design variants on the turbine test rig, multicomponent CFD simulations can be performed. In this regard, simulations of the radial intake manifold together with the nozzle ring were conducted to study inflow inhomogeneity originating

Title picture
How can the full capabilities of CFD be exploited to make the design of turbines in turbochargers even better?

The challenge associated with a multicomponent CFD simulation is the higher computational demand due to the full 360° computational domain.

3 ABB turbocharger A175-L



from the radial intake manifold – in particular, the flow performance in the diffusor within the exhaust manifold under nonaxisymmetric inflow and outflow conditions. The challenge associated with a multicomponent CFD simulation is the higher computational demand due to the full 360° computational domain that is now required because the axisymmetric flow assumption no longer holds. As is the case generally in multicomponent CFD simulations, suitable mesh matching, numerical models appropriate for multicomponent situations and reliable definition of boundary conditions are all essential.

Despite these challenges, multicomponent CFD simulations do offer the opportunity to gain insight into the flow across different components. In particular, the coupled effect at the turbine rotor exit on flow conditions in the diffusor can be studied in detail. Furthermore, because the CFD simulation of the full turbine stage from inlet flange to outlet flange corresponds to the configuration in the standard test bench measurement, numerical CFD results can be validated against experimental measurements.

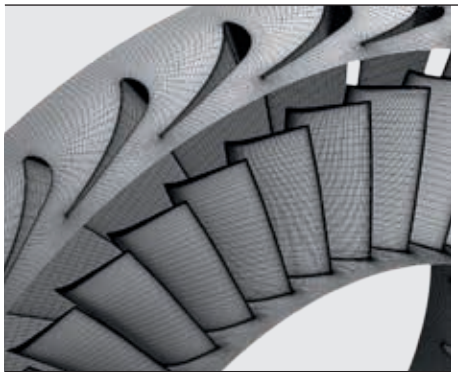
For flange-to-flange simulations however, a balance must be struck between computational effort and solution accuracy when investigating the influence of nonaxial inflow and outflow conditions.

The challenge in turbine-stage simulation arises when the intake manifold and the exhaust manifold exhibit severe turns and radial bends.

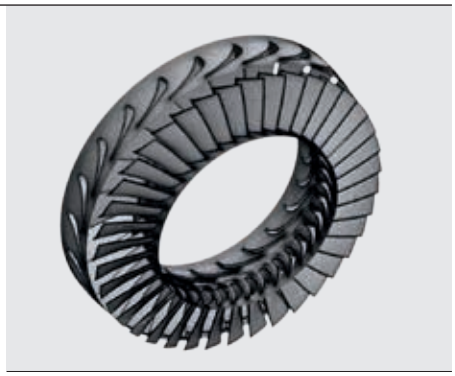
High-fidelity CFD to the rescue

Given the objective of flange-to-flange simulations, the CFD meshes, needed for the numerical calculation and the models, must be defined accordingly. A specific meshing tool that can cater for the vane and blade geometry in the turbine nozzle ring and the rotor is employed there → 4, while a general-purpose meshing tool is adopted for the intake and exhaust manifolds, where its flexibility allows it to efficiently tackle the various curved profiles.

4 CFD mesh adaptions

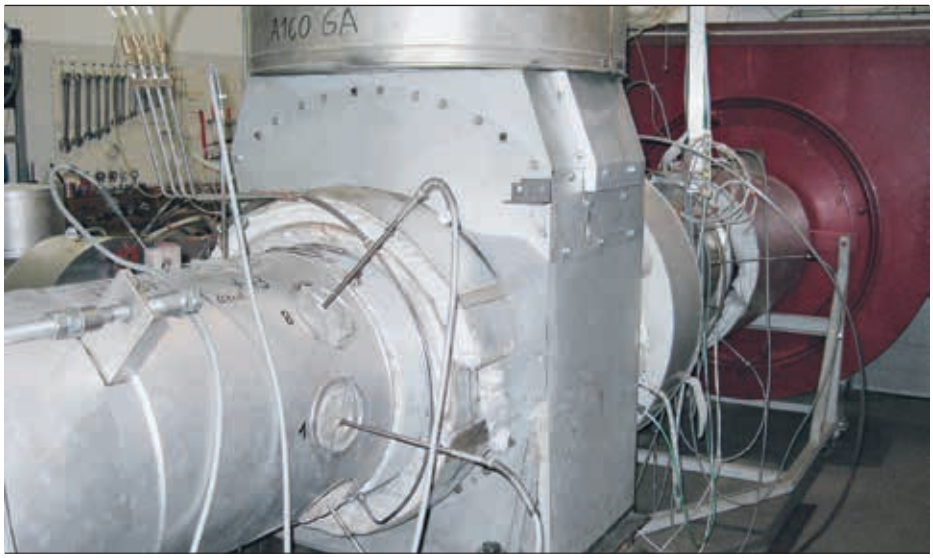


4a Nozzle vane



4b Rotor blade

5 The turbine stage on a test bench



As the CFD simulation of the full turbine stage corresponds to the configuration in the standard test bench measurement, results can be validated against experimental measurements.

In the steady-state CFD simulations, the Reynolds-averaged Navier-Stokes equations serve as the flow-governing equations. The k-ω shear stress transport model, in conjunction with a wall function approach, is adopted to predict the turbulence, onset and amount of flow separation. The CFD simulation is set up so as to avoid resolving small-timescale transient effects.

The stationary nozzle ring and rotating turbine wheel of the computational domain are coupled by a so-called frozen-rotor domain interface model. This interface model is an efficient algorithm for computing a steady-state CFD solution for stationary and rotating parts.

The CFD model and setup above is based on a widely-adopted industrial CFD platform, the accuracy of which is already verified. The computational domain typically consists of around 20 million cells and nodes. The large-scale simulations are carried out on an ABB high-performance computing (HPC) cluster so that the simulations of various components in different operating and test conditions can be conducted within a few weeks.

Physical validation

Setting up and running the simulation model is only half the story: The simulation results must be validated against physical observations, typically test measurements, to ensure that they accurately describe the physical phenomena.

In the test facility ➔ 5, an extensive list of turbine-stage characteristic quantities, including static and total states of pressure and temperature at various locations of the turbine, mass flow rate, turbine work, turbine power and turbine stage efficiency, can be measured. This provides an excellent setting to accurately define the boundary conditions in the CFD model and to form the basis for comparison and validation of the CFD simulation results.

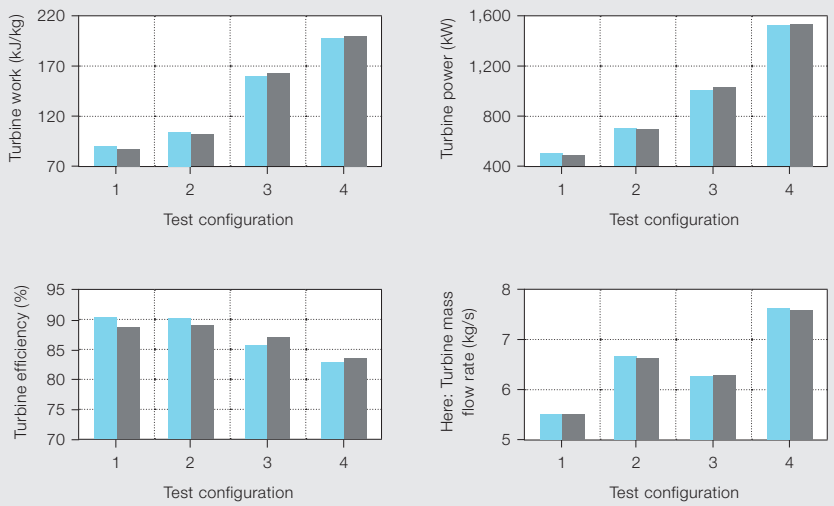
Results delivered by CFD

Different scenarios were simulated by the CFD model. These scenarios involved different designs and combinations of the nozzle ring, turbine rotor, intake manifold and exhaust manifold, as well as different operating conditions and cold-gas and hot-gas test conditions.

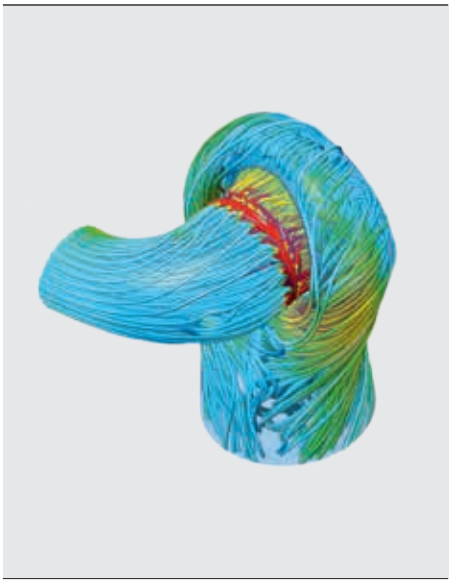
In general, there was very good agreement between the test measurements and the CFD simulations of the turbine-stage characteristic quantities ➔ 6. Because the CFD simulations are verified and validated against test measurements for a number of configurations, good insight into the flow conditions in the turbine stage from the inlet flange to the outlet flange can be gained ➔ 7.

As an example, a radial intake manifold and a 90° turn in the exhaust opening in the exhaust manifold can be simulated. With this configuration, there is a high potential for undesirable flow separation and recirculation in the diffusor region.

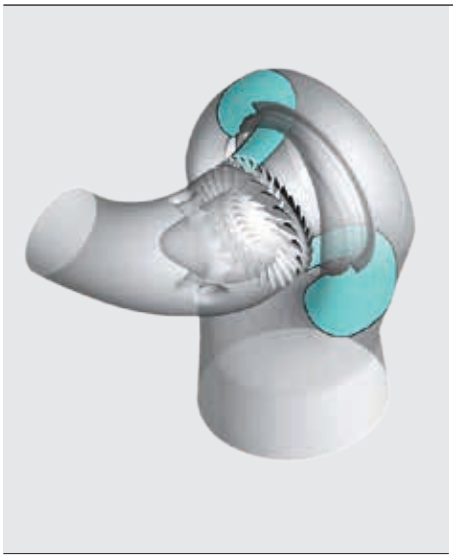
6 Comparison of selected characteristic quantities from test measurements (blue) and CFD simulation (grey)



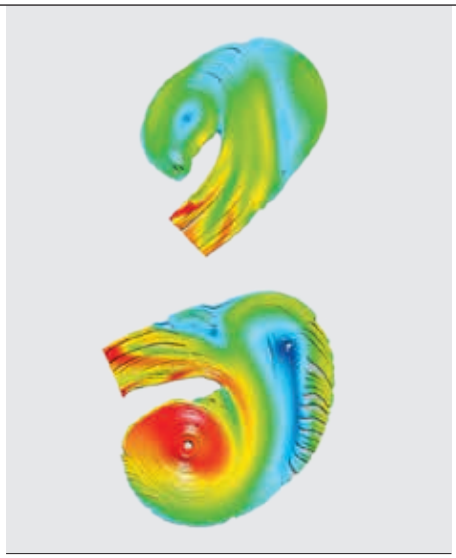
7 Streamlines from inlet flange to outlet flange. The streamline color indicates flow velocity.



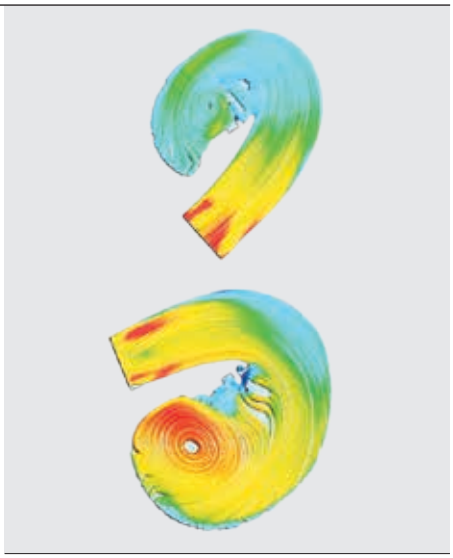
8 Streamlines for different exhaust manifold designs



8a Planes of interest



8b Undesired flow separation and recirculation in diffusor



8c Desired expansion in diffusor

As was revealed in test measurements, the performance of the turbine stage deteriorates under certain operating conditions due to nonsymmetrical inflow conditions. The drop in turbine efficiency can be captured and reproduced by CFD simulations, and the flow conditions inside the diffusor can be further analyzed by studying the CFD simulations ➔ 8. As an illustration, the plane susceptible to flow separation and recirculation inside the diffusor is highlighted in ➔ 8a. Exhaust manifolds with different diffusor designs can be simulated to identify those that avoid flow separation inside the diffusor region ➔ 8b–8c. In this way, turbine performance can be maintained even under the restrictions imposed by the radial intake and exhaust manifolds, and the adverse inflow and outflow conditions.

Outlook beyond limit

At ABB, CFD is being used to advance understanding in new areas of turbocharging technology – for example, heat transfer simulation and thermal analysis for cooling design and material selection, as well as acoustic simulation for noise reduction. In parallel, the ABB development facility – CFD simulation tools, test center and HPC cluster – are continuously being improved. Through these efforts, the next generation of turbochargers will be created.

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Mining

Our tiny blue planet is endowed with a huge variety of elements and minerals, many of which humans have found ingenious uses for. Attitudes to mining activities can be mixed and discussions are often controversial. But most material of commercial significance, including those making up the objects around us, were in some way at some point extracted from the Earth's crust, or otherwise manufactured using equipment that was itself made of such materials. Mining is a pivotal but often undervalued aspect of human existence.

ABB's presence in the mining industry spans a broad range of different fields. It ranges from the electrical supplies that keep it all powered, to mechanical items such as hoists and ventilators as well as the drives that control them. It also encompasses instruments, control and monitoring systems as well as numerous other aspects.

Issue 3/2014 of *ABB Review* will be dedicated to ABB's contribution to the field of mining.

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