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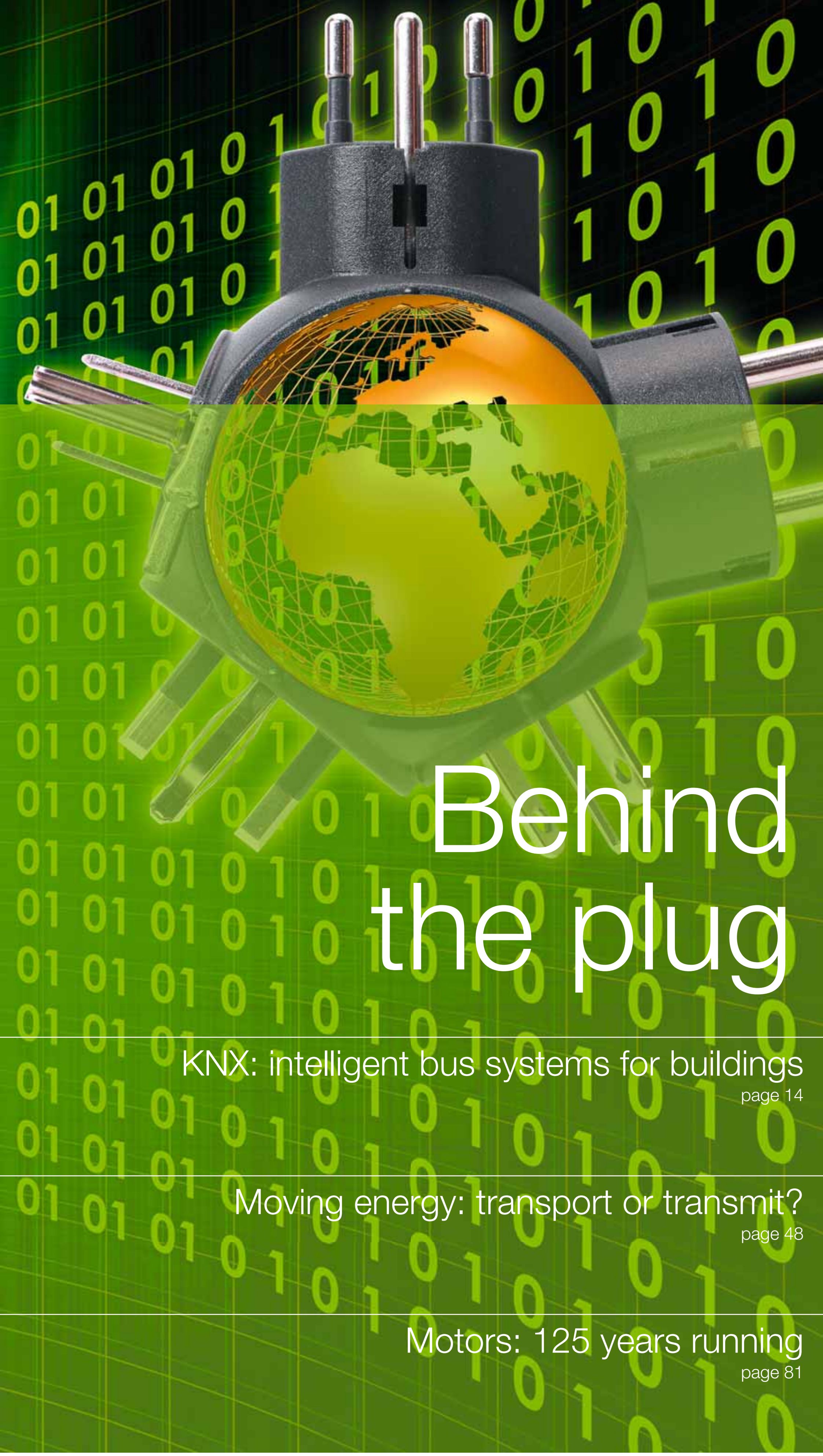

Behind the plug

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ABB

The term “plug and play” has been applied in various domains to express the ease with which new components can be added to systems. There are few areas, however, where the concept is truer to its name than in an electricity supply. When we plug in an electrical device, we expect the electricity to reach that device immediately – every time and at any time.

It is precisely because this electrical supply is so reliable that it is so easily taken for granted. This edition of *ABB Review* explores some of the technologies that make sure the electricity gets into your socket.

Powering progress – the fascinating world behind the plug

In its World Energy Outlook 2007, the International Energy Agency (IEA) forecasts a doubling of global electrical energy consumption by 2030. The share of electricity in final energy consumption is expected to rise from 17 percent today to 22 percent in 2030. These prognoses indicate that more than $ 20 trillion of investment are required.

In the developed and highly industrialized countries, the electrical grid, with its power plants and transmission and distribution systems, has grown over a century to become a mature infrastructure now requiring both refurbishment and adaptation to new sources and concepts of power generation. In the emerging countries and rapidly growing economies, electrical systems have to be substantially expanded to fulfill the economic needs of these societies.

We, as the end users, obtaining our electrical energy from the plug in our house, rarely think about the extensive infrastructure behind this plug. For us, electricity is a commodity, like so many other things in our modern society.

The variety of devices and the breathtaking complexity of the whole system behind the plug is the focus of this issue of *ABB Review*. As a market and technology leader for almost all equipment involved, we want to give you a glance at the technical development and the challenges our engineers and researchers face.

The value chain served by ABB extends from the electrical plug itself and its corresponding house installations via medium-voltage distribution and high-voltage transmission systems to generation in the power plants. Moreover, ABB contributes to efficient provision and transport of the primary energy used in power plants.

New concepts of distributed generation pose serious challenges to the grid and require more elaborate control systems than ever before. In addition, new grid topologies, efficient means of energy storage and improved power quality are issues to be solved. SmartGrids, as they are called in Europe, or IntelliGrids in the United States, are subject to broad research activities in joint university-industry teams in which ABB plays an instrumental role.

ABB technology is also pioneering applications in connecting offshore wind farms of increasing size via long subsea cables to the main grid, and our high-voltage direct current systems turn out to be a competitive alternative for the transport of energy from remote places to megacities – an ever-growing need in emerging economies.

While the grids and infrastructure systems require new control schemes and interconnections, the components in the grid, such as circuit breakers, measuring devices or transformers, experience technical progress that is rarely recognized by the public; and substations, the crucial spots in a grid, get more and more compact.

The driving forces behind this fast development stem from challenges of the modern global society: urbanization, industrialization, population growth, environmental challenges and legal constraints. ABB has built its business strategy and the technical vision on those long-term trends.

In ABB's strategy for the next five years, published in September 2007, we tackle these challenges and as part of our response increase research and development efforts to provide solutions for the future.

I invite you to join us in this issue of *ABB Review* to explore the fascinating world of technology "behind the plug."

Peter Terwiesch
Chief Technology Officer
ABB Ltd.

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Plugging in

Taking a trip behind the electrical outlet

Friedrich Pinnekamp

Nothing is more self-evident for the members of a modern society than plugging a hair dryer or computer into an outlet and expecting it to run. It took less than a century for the most versatile form of energy – electricity – to become the fully accepted and incorporated standard all over the world.

Behind that simple plug in the wall extends a breathtaking infrastructure. Join us on a short journey through this fascinating world – from the plug all the way back to the energy source – on a path that has been paved by ABB from the very first inventions to the full-fledged grid of today.

Just behind the outlet, crucial elements are providing full safety for the user of electricity: These elements are the fuses and contactors. They come in various forms for different applications in residential buildings or factories 1. While in the early years of electrification, these modules were just electromechanical devices, they have since become "intelligent", in line with the progressing information technology. Modern building blocks in house installations can communicate with each other or with higher-level automation systems and can take over control functions to optimize the use of electrical power in manifold applications.

Circuit breakers, also close to the plug and still on a low voltage level, can switch on and off large currents to supply a whole area or a large factory with energy. They also provide a safety function in case of a short circuit somewhere in the grid.

The more energy is needed, for example to supply a huge shopping center with lighting, heating, cooling or climate systems, the higher the chosen voltage level for distribution. To go to medium-voltage distribution, transformers and circuit breakers combined with measuring devices are needed; these are then put together in medium-voltage substations. Cables transport the electricity from those substations to the users.

If you don't see those substations (which are sometimes small containers along the street) it is for good reason: The development of compact and integrated functions in smaller units is ongoing. Ever-increasing automation and control of these substations contributes to the trend toward self-controlled systems.

There are two means of electrical power generation. In one method, local units such as diesel generators, wind mills, fuel cells and small power plants generate power for a close-by user. With the other established method, large central power plants run on hydro fuel, coal, oil and gas, or nuclear fuel to generate between several hundred megawatts and some gigawatts of electricity.

The large central power station requires transport of electrical power over significant distances and subsequent distribution into several channels to reach large factories, supermarkets or whole cities, for example. Transport over long distances is preferably done at a high voltage level to reduce the loss of energy in the lines. Power substations are required to convert the voltage from some ten kilovolts at the generator output to the high level of several hundred kilovolts for transport, and then back to the lower voltage level for wider distribution at the end of the line. Large transformers and powerful circuit breakers are the heart of these substations, built either as air-insulated systems on the "field" or more compactly as gas-insulated packages.

1 Devices close to the plug to provide safe electrical power

2 Control of a power plant to optimize production

It goes without saying that substations are highly automated. They are the nodes of an automation system that cover large areas, often whole countries and sometimes cross-border interconnections. With increased linking of national grids, the stability of a huge collection of power plants and consumers must be guaranteed – this requires wide-area monitoring and management.

Both methods of transporting energy over long distances, with alternating current (AC) or direct current (DC), have their optimal applications. Progress is made in both flexible AC transmission systems (FACTS) and HVDC light.

The infrastructure behind the plug is indeed fantastic – let's not take it for granted!

Local generation (that is, closer to the consumer) is a challenge addressed by the new concept known as "smart grids". With smart grids, the world is not simply separated into generators and consumers; here a consumer can also be a generator, providing the grid with the surplus energy of his local generation device. The management of such a system is a complex task that engineers have just started to work with. In fact, smart grids and wide area networks are tightly interlinked, which adds significantly to the complexity.

In the value chain of electrical power, the generation itself is essential, of course. Power generation is also the place where valuable energy is lost in the conversion from thermal to

3 Obtaining the primary energy for electrical power generation

mechanical to electrical energy. While basic physical principals limit the conversion efficiency, it is still optimal power plant management that determines how close one can get to these physical limits. Coal-fired steam power plants, for example, need coal to heat a boiler and generate very hot steam at high pressure. The high-pressure steam enters a steam turbine, which then drives the electrical generator. While the generator does not "know" how the steam was produced, it is essential for the operator of the plant to know and to do it in the most economical way 2.

The value chain goes even further back to the place where the coal or the oil and gas are exploited. The efficiency of the production of this primary energy has a great influence on the price of electricity and on its long-term availability 3.

The infrastructure behind the plug is indeed fantastic. Before the energy can be taken from the plug, it must be converted from primary energy to steam or directly to electricity in solar cells or wind mills. It has to be transformed into high voltage and back to low voltage with an optimally managed flow in smart grids or large interconnections, all the while ensuring the utmost safety and reliability for the countless ways in which it will be used – let's not take it for granted!

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Electrical energy

The challenge of the next decades

Bernhard Jucker, Peter Leupp, Tom Sjökvist

The electricity industry is driven by a number of different forces, and it faces a series of challenges that will change the way that electrical energy is produced, distributed and used. With demand growing at a constant rate and with most of that growth taking place in developing countries, the regional differences in the way electricity is used are likely to be accentuated. In the mature economies the aging infrastructure poses a challenge and the request for technologies that protect the environment and reduce the energy intensity is high. In the developing and fast-growing economies, the vast need for electrical energy drives huge investments in new infrastructure for generation, transmission and distribution.

Although the energy mix for power generation is not expected to change significantly, those countries that increase the amount of renewable energy in their mix will need to address grid reliability. Transmission and distribution grids in many parts of the world are operating close to capacity and although new grids are being built in the rapidly growing Asian economies, they are not being built fast enough to meet the escalating demand. To reduce local energy shortages or provide a better optimization base for utilities, either inter-connections between grids will be necessary or other local resources for generating electricity have to be promoted.

The top priority for all countries will be to ensure a reliable supply of electric power. The cost involved in refurbishing grids and new grid installations is a major challenge. This challenge is getting harder for the equipment manufacturer due to the shortage of materials used and the fact that ageing assets require more and more maintenance. To reduce operating costs and increase output there will be a tighter focus on minimizing power losses and on changing the way energy is used and marketed.

Political drivers

In most emerging economies and in some mature economies, the demand for electricity increases in relation to growing gross domestic product (GDP) per capita 1. Governments attempt to keep pace by providing a functioning electrical infrastructure that can extend over vast geographic expanses, as in China and India, or across national borders, as in Africa or the Middle East.

In mature economies, investment in power networks consists mainly of bottleneck removal and network improvements to secure supply reliability and prevent blackouts. Deregulation was introduced to encourage investment in electrical infrastructure. This has not materialized, with the result that an imbalance exists between lacking generation capacity and increasing consumer demand in many parts of the developed world.

The fact that critical applications like hospitals, the manufacturing and process industries, and Internet and telecommunications infrastructure are dependent on electricity makes supply reliability a priority for many countries. Whether the primary energy sources are nuclear power, wind energy or coal, for example, in those cases where generation and consumption are not collocated, countries must trigger investment in the transmission and distribution network to facilitate the delivery of larger volumes of power.

The top priority for all countries will be to ensure a reliable supply of electric power.

Network interconnections are driven by several key political factors. First, the need for supply security is strongest in those countries where there is a shortage of power generation resources. Getting connections to other grids could help. Second, interconnections make it possible to stabilize a national grid without making a major investment by using foreign capacity reserves. And third, interconnections in some large political structures like the European Union are a logical consequence of the political integration of neighboring nations.

An important argument for cross-border operating utilities is the increased flexibility and the better options to plan new generation capacity.

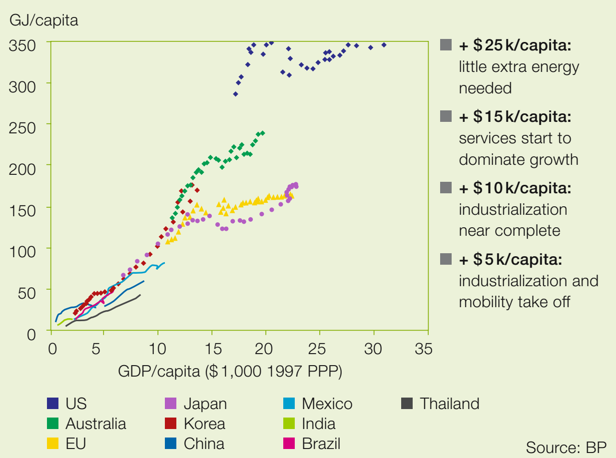
Environmental issues are also driven by political considerations. The Kyoto Protocol and other international accords are driving new types of energy generation, in particular renewable energies with low CO_2 emissions. These agreements have a direct influence on the types of energy selected for state subsidies and on the technologies on which companies focus their research and development programs.

Policies intended to stimulate the growth of renewable energy can have diverse effects. A decision to replace five or ten percent of a country's electrical supply within a short timeframe can only be achieved by building large offshore wind parks. ABB recently got an order to connect the world's largest windpark in the North Sea to the German electrical grid. Additional generating capacity will be necessary to ensure that there is sufficient backup power and that grid stability is not weakened. On the other hand, wind parks are not always popular. People do not usually like wind turbines close to their homes and often oppose the building of new nuclear power plants, even though both alternatives are environmentally friendly with respect to CO_2 emissions and global warming.

Different regions prioritize different aspects of the environment. While the presence of distribution lines in the streets of towns and cities is not acceptable in Western Europe, it is not an issue in the United States and other parts of the world. For transmission lines the issue of the "right of way" is significant[1)].

The regularity and effects of blackouts – as in Europe in 2003 – have triggered

1 The connection between gross domestic product and energy consumption per capita reflects on the status of development of a society



Footnote

[1)] See "Transport or transmit?" on page 44 of this edition of *ABB Review*.

A complete supply chain

a political debate about the reliability and robustness of electricity networks. In some countries new legislation is imposing heavy financial burdens on utilities that fail to deliver power to consumers; in others, utilities have made agreements with large industrial consumers to shed load in overload conditions in order to secure network stability and prevent large-scale blackouts.

Attempts to control the power factor of industrial and electrical equipment are also making progress. Legislation, energy taxes and information campaigns have all influenced customers into selecting variable-speed drives and high-efficiency motors, and consumers into choosing energy-efficient home appliances [1].

Economic drivers

Strongly connected to economic growth, especially in the rapidly emerging economies, is the demand for electrical energy. The International Energy Agency (IEA) estimates that net electricity consumption in the emerging economies will grow at an average rate of about 4 percent a year between 2007 and 2030 2. In contrast, demand in the mature economies is predicted to rise by an average of 1.5 percent a year, and in the transitional economies of Eastern Europe and the former Soviet Union (EE/FSU) by an average of 3.1 percent. China and the United States are expected to lead the projected growth in consumption, adding almost three and two billion kilowatt hours, respectively, to their annual net consumption levels over the 23-year period 3.

Predictions for growth in net consumption in the emerging economies are based on projected increases in GDP and population. GDP growth in turn is dependent on access to reliable supplies of electricity. Because of the connection between reliable electricity supply, GDP growth and rising living standards, many emerging economies are making efforts to increase the capacity and reliability of their power networks.

In China and India this is leading to the construction of new power plants in remote locations close to primary energy sources. New transmission lines with the capacity to deliver large volumes of power are therefore required[2].

In the United States strong economic growth throughout the country is increasing the need for more generating capacity, mostly provided by upgrading existing plants. Demand for power is particularly strong in the commercial sector where average increases of 2.4 percent a year are offsetting efficiency gains in electrical equipment. Growth in the industrial and residential sectors is expected to be moderate.

Western Europe and Japan are expected to have the slowest growth in demand at 0.4 and 0.6 percent, respectively, in the residential sector, and 0.8 and 0.9 percent, respectively, in the commercial sector. Static or slightly declining population levels, expansion of information and communication technology (ICT) infrastructure, and the switch to economical heating and cooling devices are the main reasons for the flat demand curve.

The vast growth in demand for electrical energy is expected to continue over the next two decades and is estimated to require an investment of $ 10,000 billion in new electrical infrastructure, about half of which is needed for transmission and distribution systems.

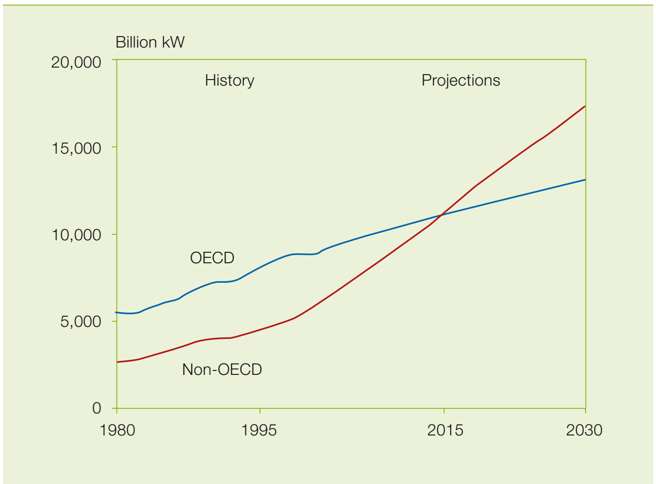
Many emerging economies are making efforts to increase the capacity and reliability of their power networks.

In mature economies the tendency is to get as much energy as possible out of the existing system. Building new transmission lines is difficult for a variety of reasons, an important one being the "right of way" issue. There is little incentive for utility companies to invest in transmission and distribution infrastructure, as long as the investor is not the one who profits from the investment. It is more economical for them to squeeze more capacity out of existing assets.

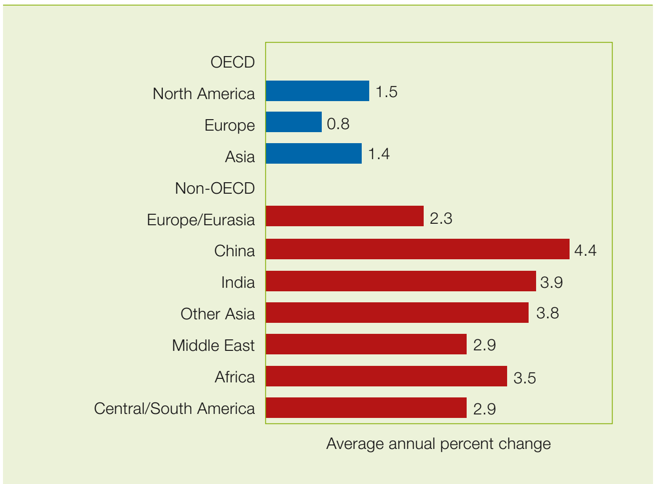
Footnote

[2] See "Transport or transmit?" on page 44 of this edition of *ABB Review*.

2 World electric power generation by region (Source: IEA *World Energy Report 2007*)



3 Projected growth rates in electricity generation for OECD and non-OECD countries (Source: IEA *World Energy Outlook 2007*)



A shortage of electricity in periods of high demand can lead to brownouts or blackouts. A recent study by the Union for Coordination of Transmission of Electricity (UCTE) in 2005 estimates that in 2015 there will be insufficient reserves of electrical power in all European countries. The report assumes that current plans to increase generating capacity will be implemented. The most economical solution to an energy shortage is to import power from a neighboring country. Connection to an adjoining grid is an efficient way for a country to stabilize its grid if spinning reserves are insufficient.

In mature economies there is a tendency to take electricity supply for granted. This was given a severe blow in 2003 when a series of widespread and high-profile blackouts drew attention to the vulnerability of electrical infrastructure. It led to the realization that there is a need to replace or upgrade ageing assets on a large scale in the short to medium term.

There was a similar wakeup call in China. Three-quarters of the electricity consumed in China is used for manufacturing and heavy industry. When power shortages occurred in the summer of 2004, some 6,400 industrial plants in Beijing alone were shut down for a week and their operations staggered for the duration of the summer to avoid consumption peaks. Unless investment in electricity infrastructure keeps pace with demand, shutdowns and rolling blackouts could have a significant and detrimental effect on the country's economy.

China's 11th five-year plan targets an increase in generating capacity of 570 gigawatts by 2010. This is equivalent to an increase of roughly eight percent a year and will require annual investments of $ 20 billion to $ 30 billion. It appears, however, that building more power plants will not solve all of China's electricity problems. Equally important is the construction of transmission lines to link the plants to consumers. The State Grid Corporation of China estimates that investments of $10 billion a year will be needed to expand and upgrade the country's power transmission grid.

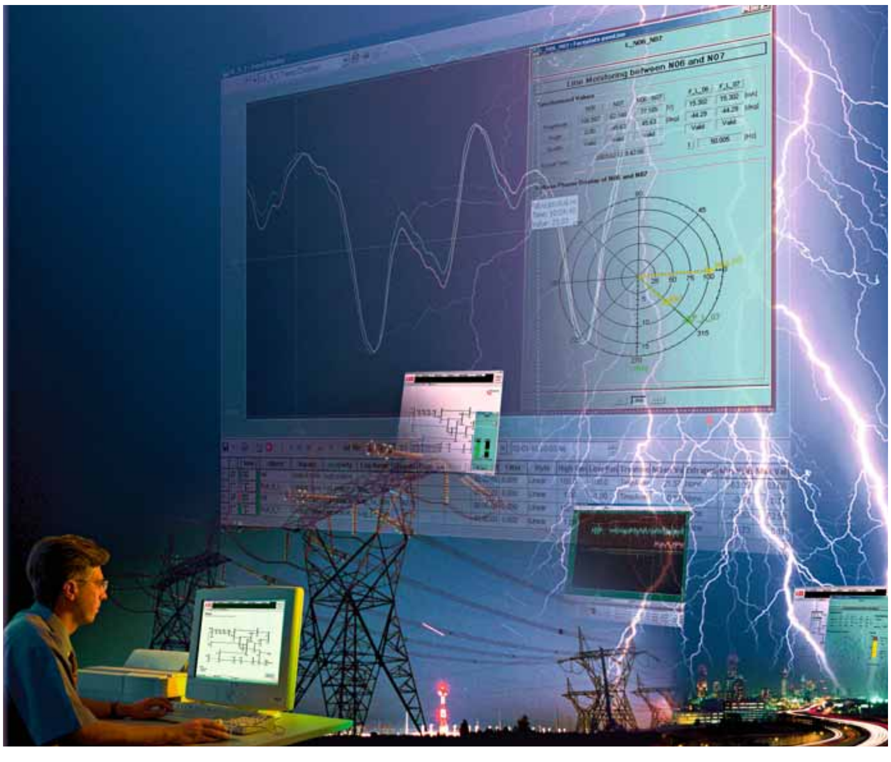
Some countries have introduced penalties for utilities that fail to meet demand. In Sweden, electric utilities have to compensate households with a sum equivalent to approximately one month's electricity consumption for every day that the household is without power. This is a strong incentive for utilities to improve grid reliability.

Many utilities now see reliability as one of their most pressing concerns. The impact of poor reliability on society as a whole can be crippling. The blackout on August 14, 2003 in the United States is estimated to have incurred costs and lost revenues of $ 7 billion to $ 10 billion, and is attributed, as are most large-scale blackouts, to underinvestment in transmission and distribution capacity and the use of outdated technology and simply wrong operation procedures.

Like reliability, the quality of the power delivered is increasingly driven by economic considerations. Some industries, such as printing and petrochemicals but also hospitals and other critical systems, require high levels of power quality. A Nordic Council survey estimates that the damage caused by a voltage sag (50 percent, 200 ms) for an average industry is as high as $ 4.50 per kW installed. The demand for power quality is particularly strong in mature economies with extensive amounts of sensitive ICT infrastructure, but is likely to become a global issue in the decades to come.

Attempts to reduce system losses are also driven by environmental factors. Transmission and distribution systems tend to lose 6 to 7 percent of the electricity they transport. Approximately 70 percent of those losses occur in the distribution system, which is more extensive than the transmission system and operates at a lower voltage (losses in lines are inversely proportional to the square of the voltage, ie, doubling the voltage reduces losses to a quarter of their original value). Losses of more than 30 percent are estimated for developing countries, although it is important to distinguish between technical losses and commercial losses (the latter cannot be accounted for and are usually due to illegal connections).

Technical losses are rarely above 20 percent. Technologies such as high-quality transformers and reactive power compensation can reduce them to 5 to 7 percent. High levels of commercial losses can be devastating for system operators: If they cannot collect revenues, they cannot generate sufficient capital for investment.



A complete supply chain

It is not only utilities that are keen to reduce losses. Electrical energy savings have a direct impact on the bottom line of industrial plants, commercial businesses and households. This drives the demand for energy-efficient electrical equipment like motors, drives and consumer appliances.

Electrical energy savings have a direct impact on the bottom line of industrial plants, commercial businesses and households.

The market naturally expects the cost of new grids and grid components to be as low as possible. With the price of raw materials like copper rising, their replacement with low-cost or better alternatives is an ongoing issue. Similarly the replacement of hazardous materials and the avoidance of penalties or taxes for excessive greenhouse gas emissions are strong economic drivers.

Technology drivers

Many new technologies, especially those for ICT devices and systems, require substantial amounts of energy. The growing number of new consumer products and more powerful home computers also use large amounts of electrical energy. In Germany, the estimated energy requirement of ICT devices is expected to grow by about 4 percent a year and account for 11 percent of the country's energy consumption in 2010.

New technologies for industrial and commercial applications like integrated heating and cooling systems in buildings, improved battery technology for hybrid vehicles, and the widespread introduction of high-speed trains will increase the demand for efficient electric power. Technological developments in wind power will change energy flow patterns in grids, as will new types of power generation on the low-voltage side and large-scale wind farms.

Progress in static var compensation and power storage technologies will enable new sources of electrical energy to be connected to existing grids. New types of batteries that are more compact than conventional lead-acid technology are already making an impact. For instance, the 40 MW battery at Fairbanks, Alaska, provides backup power for up to seven minutes for a community of 80,000 people [2]; and a new compact lithium ion substation battery with greater capacity and reliability is operating successfully in a pilot installation in Sweden. These installations are rather the exceptions and did not find a wider application so far. Flywheels, compressed air, pumped hydropower or compressed air storage are other means of storing energy through conversion.

Another energy storage method is hydrogen. Electricity is supplied to an electrolyzer, which divides water into hydrogen and oxygen, its two constituent parts. The hydrogen can then be stored and reconverted into electricity by fuel cells when needed. The overall efficiency of this storage method is currently rather low at about 25 percent. It remains to be seen whether hydrogen will replace electricity as a better means to transport energy. Major progress in the technology is not expected within the next few decades.

Phase-shifting transformers and series compensation are long-established methods for increasing power transfer in electrical grids. Power electronics have made it possible to control grids and new FACTS (flexible AC transmission systems) are improving controllability [3]. New concepts like the unified power flow controller (UPFC) and the variable frequency transformer (VFT) have to show their customer acceptance yet. Monitoring systems like phasor measurement units are slowly being installed in power networks, which will, when fully deployed, increase the possibility of operating a system close to its limit [4].

New technologies will also improve maintenance. The switch from oil-based to dry insulation and from spring drives to electrical drives in circuit breakers are examples, as is the introduction of information technology into maintenance processes. Online analysis of primary equipment such as transformers is facilitated by software that assesses the condition of the equipment in real time. Risk analysis software for the preventive maintenance of critical grid components is also available and under continuous development [5].

Technologies that save energy or improve efficiency are becoming more widespread [6]. Low-loss and energy-efficient power semiconductors are reducing losses in the grid, and material processing like laser-cut sheet metal for transformers and improved material properties may result in additional efficiency gains. Traditional lightbulbs are being replaced by electroluminescent lighting and more recently by bright LEDs. And continuous reductions in energy loss are being achieved by advanced motors and power-electronics-based variable-speed drives.

The use of superconducting materials is another way to reduce losses in power grids. Research laboratories are making progress and there are now several types of superconducting materials available, of which magnesium diboride is a recent addition. Efficient cooling and an interface with existing 400 kV systems (a low-voltage/high-current system to a high-voltage/low-current system) and improved system characteristics will have to be developed before real progress with superconducting transmission can be made.

Compact circuit breakers and gas-insulated switchgear have reduced substation footprints and made it possible to build substations indoors – important factors in urban environments and megacities where space is expensive and in short supply[3] [7]. By replacing oil-paper insulation with cross-linked polyethylene (XLPE) insulation, the viable length of AC cables has increased by a factor of two and made underground high-voltage direct current (HVDC) cables economical for long distances [8].

New HVDC technology reduces the footprint of existing HVDC by a factor of three [9]. This is especially important for applications where space is critical. Some electrical equipment footprints are determined by the noise level they inject into the environment. New technologies have reduced noise in shunt reactors by 15 dB in the last 20 years.

Technical progress with new materials makes for better applications. Dry materials like XLPE are replacing oil and other wet materials; they reduce the risk of fire and enable equipment to be located closer to buildings. The standard epoxy resin commonly used as insulating material is being replaced by modern thermoplastics that bring more flexibility into manufacturing.

Information technology has opened up new ways for electricity to be traded as a commodity. Utilities are equipping households with meters that measure hourly consumption, and hourly trading is on the agenda to enable consumers to buy the cheapest, greenest or locally produced power. Reserach and development initiatives on “smart” or “self-healing” grids that improve supply reliability are also driven by advances in information and communication technology[4].

Prepared for the future

ABB, as a technology and market leader for all the issues discussed here, is very well positioned to contribute cutting-edge technology to the world’s major energy challenges. ABB’s local presence in all the markets gives customers the valuable advantage of fast and focused service. ABB works together with its customers to find the best solutions tuned to their local needs and to develop systems that work effectively across borders, whenever global approaches are appropriate.

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Footnotes

[3] See “Substation evolution” on page 34 of this edition of *ABB Review*.

[4] See “When grids get smart” on page 44 of this edition of *ABB Review*.

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Intelligent energy efficiency

How KNX bus systems control our buildings

Hans Rohrbacher, Christian Struwe

Modern information and automation technology has become an integral part of human life in recent years – so integral, in fact, that its presence is often taken for granted. But for a long while, two central areas of everyday life – that is, homes and office buildings – have been technologically neglected. Electrical installations in a building were mainly limited to the selection and quantities of the appropriate switches and outlets that suited the design of the house. The average user was usually not aware of the technology behind it.

Today this is no longer true: It has become very easy to fit and use intelligent installation systems. They offer unimagined flexibility, safety and energy savings, features that no one wants to do without.

The KNX system enabled the introduction of the latest technology into electrical installations Factbox. The functionality of the individual KNX device not only covers the entire application area of comparable conventional installation equipment, but also offers possibilities that are not enabled – or are enabled only at high costs – by the conventional technology.

Communication between the KNX equipment of different trades allows for multi-use of equipment and transmission routes, thus saving resources and also providing functions that would otherwise be achieved only via costly interfaces, and additional devices and cabling.

Factbox KNX: a standard with increasing acceptance

For more than 15 years, ABB STOTZ-KONTAKT in Heidelberg and Busch-Jaeger Elektro in Lüdenscheid have been developing and producing electrical installation equipment that is interconnectable via the KNX bus system. The KNX bus system is compliant with the European standards CENELEC EN 500090 and CEN EN 13321-1, as well as with the international standard ISO/IEC 14543-3. In China, the bus system has been integrated into the national set of standard specifications known as Chinese standard GB/Z 20965.

The KNX Association is a group based in Brussels consisting of leading European manufacturers of installation equipment as well as companies from the United States, the Middle East and China. The KNX Association advances the KNX standard, which is completely open and platform-independent and enables a manufacturer- and trade-independent interoperability.

KNX devices are used in many areas: Electricians use it for almost all installations – ranging from the switching and dimming of artificial light to the control of audio and video equipment – as well as in all applications within buildings, whether they are single-family homes or high, multi-storey buildings.

The measures to reduce energy consumption and efficiently use energy in buildings that are proposed in most publications today suggest the use of thermal protection of buildings and the use of efficient heating plants and cooling plants to reduce energy consumption.

The following examples show how the use of KNX equipment offers further possibilities for both energy savings and energy efficiency. Each individual measure does not appear to offer significant energy savings; however, the measures as a whole are not negligible. The enormous increase in functionality achieved through integration of the KNX equipment is the major incentive for users of such systems.

Lighting control

One of the core applications of electrical installation technology is the switching and dimming of lights, as well as the distribution of the electrical energy. A simple measure to prevent any unnecessary energy consumption is the automatic disconnection of any illumination after a defined period of time. Thus the light that was left on in the basement will no longer be a problem. This possibility is provided by the application software itself as implemented in the KNX switch actuator ABB STOTZ-KONTAKT. In addition, a sophisticated timing switch program can be established via an application component that makes it possible to switch on and off a single light or a group of lights, and that defines specific brightness levels. Since the available devices are interconnected, no additional cabling is required between the application unit and the various lamps – even if a great number of the single lamps are individually switched or dimmed.

Another possibility is to switch on the light only when needed. Motion detectors 1 are the preferred solution, as they react to minimal movements and are able to recognize whether there is a person in the room.

The KNX motion detector also has a feature to keep the illumination at a constant level, irrespective of external brightness. It can also automatically switch off the lights in response to external brightness.

The motion detector also has an alerting function; ie, it is able to react to major changes in movements. This function could be used in applications such as an alarm system.

A movement-dependent illumination control can also be established via an infrared motion detector. Busch-Jaeger offers a broad selection of wall-mounted and flush-mounted detectors 2.

Compared to the motion detector, the Busch watchdog will only switch the light on and then off again as soon as there is no one in the defined control range of the motion detector. It is also possible to adjust the time period during which the light is activated after a person has triggered it (so-called follow-up time).

Shutter control

Another major KNX application refers to the control of rolling shutters and

1 KNX motion detector by Busch-Jaeger Elektro

2 Busch alerter 220 EIB Professional Line

Distribution

jalousies (ie, Venetian blinds). ABB's KNX shutter actuators 3 provide the possibility of simple automated sun protection. The controls process the following information: "The sun is shining," "Someone is present in the room," and "It is wintertime/summertime." During summer, the jalousies will completely close when the sun is shining and no one is in the room, thereby darkening the room in order to prevent unnecessary heating. If someone enters the room, the slats open just enough to lighten the room. During wintertime, the opposite control is employed. When the sun is shining and no one is in the room, the jalousie will open completely in order to better use the sun radiation for additional heating. If someone enters the room, the jalousies will be closed to a position to prevent any glare.

In order to assess the external brightness, conventional sensors may be connected via conventional interfaces, eg, 0…10V, to the KNX analog inputs. If an adjustable level is exceeded, the corresponding message will be generated, which then triggers the KNX shutter actuators. Alternatively, a KNX weather station may be used that, in addition to evaluating information on brightness, is also able to evaluate information on wind, temperature and rain. A specially adapted combined sensor is available for this and generates the corresponding messages.

The shutter control unit offers even more possibilities for an optimum adaptation of the mounting height and the blade angle 3b. This apparatus, with the size of only two standard sections, allows optimum positioning of each individual jalousie on all sides of the building where the sun is shining. This optimum positioning is the result of evaluation of the current date and time, geographical width and length, alignment of the individual building sides, blade geometry and the message "The sun is shining." For this evaluation, permanent shadow sources, such as neighboring buildings, and temporary shadow sources, such as broad-leafed trees, are taken into account.

The KNX motion detector has a feature to keep illumination at a constant level.

Heating control

One example of the overlapping functionalities of the KNX system is the temperature control for individual rooms in connection with the boiler control 4. The control elements shown for switching and dimming of the light and for moving the shutters up and down are also equipped with a temperature sensor. This sensor registers and displays the room temperature, compares it to the current nominal value and submits the set value to the electrically controlled valve that is also connected to the KNX system.

In the application unit of ABB STOTZ-KONTAKT or in the room panel and control panel of Busch-Jaeger Elektro, a temperature profile and time profile have been defined; they send different set point values to the thermostat depending on the time and the day of the week. Thus the bathroom may be heated to a pleasant 24 °C long before someone wakes up. On the other hand, the application unit or the room panel or control panel may switch the temperature control to night operation in the evening. The rooms will be heated only if necessary, and the room temperature will be controlled to the required comfort level. Independent of these controls, manual manipulations are always possible.

The KNX boiler control provides another possibility for energy savings. In the case of a conventional boiler control, the entry temperature of the heating is controlled only on the basis of the outside temperature, whereas the boiler control that is connected to the KNX system will check the valve drives that are also connected to the KNX system and will determine their position.

The valve position provides the information to the boiler control on how much heating energy is required in the rooms and whether the entry temperature may be reduced below the current value. This prevents any undesired losses due to an entry temperature that is too high.

Room and Control Panel

The Busch-Jaeger Room and Control Panel 5 can also control complex processes, such as lighting scenarios, attendance simulations and individual room temperature control, in a simple manner via the KNX system.

3a Jalousie control für SMI drives

3b The ABB Stotz jalousie component

4 Solo RTR 6128-xx

5 Multifunctional Room and Control Panel

6 LED WaveLINE and switch

7 Gateway to the KNX system

The panel possesses a graphic-compatible LCD screen with an integrated background light. It enables activation of up to 210 switch and control functions on various display pages that have been programmed to customer specifications by the installer. During an absence, the room temperature can be automatically lowered to save energy.

Various pre-programmed light scenarios offer significant energy savings, since the room lighting can be immediately adjusted to the actual requirements (eg, reading, watching TV) by simply pressing a button. This means the conditions are active only under the circumstances where they are currently required.

Busch radio control

With the new Busch radio control system, open windows can be localized via the Room and Control Panel or via the LED Busch-WaveLINE 6. If some windows are open, the heating may be turned down automatically by the KNX system in order to save energy. This system can be easily installed in existing windows.

For the latter case, the LED WaveLINE is connected to the home network system via a KNX bus coupler. If one or several windows are tilted or completely open, the room heating may be reduced or the entire heating system can be switched to night control, if desired.

Remote control

Gateways enable remote access to the KNX system 7, allowing the system to connect with an analog or digital telephone network, a local network or the Internet.

Take, for example, a house in the countryside that is used only during the weekend: The heating for some rooms can be controlled to a comfortable temperature from Friday evening to Sunday evening. Should the planned visit to the weekend house not take place, a simple phone call or mouse click is sufficient to switch the heating to minimum standby operation.

The Busch-Jaeger Room and Control Panel can control complex processes, such as lighting scenarios, attendance simulations and individual room temperature control, in a simple manner via the KNX system.

Application-independent basic functions

Apart from application-specific equipment, the product range of ABB STOTZ-KONTAKT and Busch-Jaeger includes various generic equipment, eg, binary inputs and actuators. Binary inputs make the relevant information available to the KNX system. This information can then be transformed by actuators, for example.

Such equipment enables further functionalities that help reduce energy consumption in buildings. After closing hours in offices, the actuators – automatically controlled by a timer – can turn off the sockets that are used for devices with standby functions. This may refer to printers, access points for the WLAN or even the coffee machine. In a residential building, a central "off" button may activate the same function. In addition to the reduction in energy consumption, the potential danger of unattended electrical equipment is reduced.

Prepared for the future

Generally speaking, functional buildings require major renovation after a period of approximately 10 years. Such renovation often implies a modification of the electrotechnical infrastructure. Instead of refurbishing the complete electrical installation and adjusting it to the new requirements, in most cases it is sufficient to reprogram functionalities and to install some new devices. KNX systems not only secure the comfort, flexibility and environmental compatibility of today's buildings, but also secure the economic efficiency of future upgrades.

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A matter of timing

An active protection device that reacts quickly to internal arcing enhances operator safety and equipment availability

Carlo Gemme, Michele Pasinetti, Renato Piccardo

Switchgear arcing can have serious consequences. It only takes a few milliseconds for an arc to form, but the energy level built up throughout its duration is astounding, and can result in serious injury or, in very rare cases, even death. Numerous arc protection devices exist to reduce the duration of the fault current feeding an arc, but these do not necessarily prevent damage from occurring. The damage that results from an arcing accident depends on the arcing current and the time taken to intervene and extinguish it, and of the two parameters, only time can be influenced.

ABB's product portfolio contains several reliable protection systems, some of which can extinguish an arc in less than 50 ms. This portfolio has been further enhanced with what is known as an Arc Eliminator. For switchgears, this device is an extra safety feature, much like the airbag in a car, that combines the positive characteristics of other ABB protection devices. It is a fast-closing earth switch that can make a complete busbar short-circuit in less than 5 ms. It is defined as an active protection system that has been integrated into ABB's UniGear switchgear. In addition to speed, the Arc Eliminator gives important savings in terms of repair cost and downtime.

Switchgear internal arcs may happen because of defective insulating materials, improper bus joints, poor maintenance, animal intrusion, or simply human error. But when they do occur, and if there is little or no protection in place, the resulting damage can often be extensive or even fatal [1]. An arc[1)] causes a rapid rise in the temperature of the surrounding air and in the pressure inside the enclosure, and the energy release is equivalent to that of an explosion.

The occurrence of such a fault leading to personal injury in modern medium voltage air insulated switchgear (AIS) and gas insulated switchgear (GIS) is extremely rare. This is mainly because operators are well protected against internal arcs by passive protection systems, such as the switchgear structure. In other words, the switchgear enclosure is capable of withstanding the pressure and heat generated by the arc, and the installation of an exhaust duct directs the hot gases away from the operator working area 1. Additionally, the duration of an arc, and hence the damage it causes, is limited by the choice of an appropriate relay protection system.

Prudence and certain international standards Factbox say that people should not work on, or even be near, exposed live components. However, no matter how carefully safe work practices are followed, risks exist when it comes to electrical equipment. There will always be occasions, such as when a problem cannot be uncovered by troubleshooting the equipment in a de-energized state, where it is necessary to work on energized equipment. On these occasions, a conventional protection relay's driven breaker operation requires a minimum of between 100–200 ms to extinguish a fault. During this time, operator safety is guaranteed by the switchgear structure. Unfortunately, the same cannot be said for the electromechanical equipment in the compartment where arcing occurs. The first 120 ms of the fault is considered the dynamic phase of arcing during which high pressure develops and hot gases expand. These combine to completely destroy whatever was in the

Factbox Standards defining electrical safety requirements in the workplace

The foremost consensus standard on electrical safety is the US NFPA 70E "Standard for Electrical Safety Requirements for Employee Workplaces" [2]. In this standard, it clearly states that workers should not work on or be near exposed live parts except for two reasons, as stated in NFPA 70E-2000 Part II 2-1.1.1*):

- When de-energizing introduces additional or increased hazards (such as cutting ventilation to a hazardous location)
- When equipment design or operational limitations (such as when voltage testing is required for diagnostics) make it otherwise difficult

In the US, non-adherence to these regulations and practices is considered a violation of law and is punishable by a fine and/or imprisonment. In Canada, a similar standard, "Arc flash/electrical safety in the workplace," CSA Z460, which addresses worker safety with respect to internal arc or flash hazard, is currently being defined.

Footnote

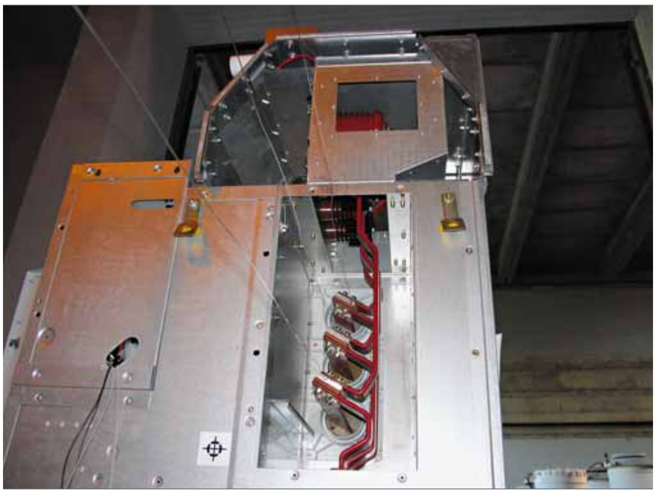
*) More detailed information can be found at http://ecmweb.com/ops/electric_top_five_keys (October 2007).

1 The switchgear enclosure is capable of withstanding the pressure and heat generated by an arc

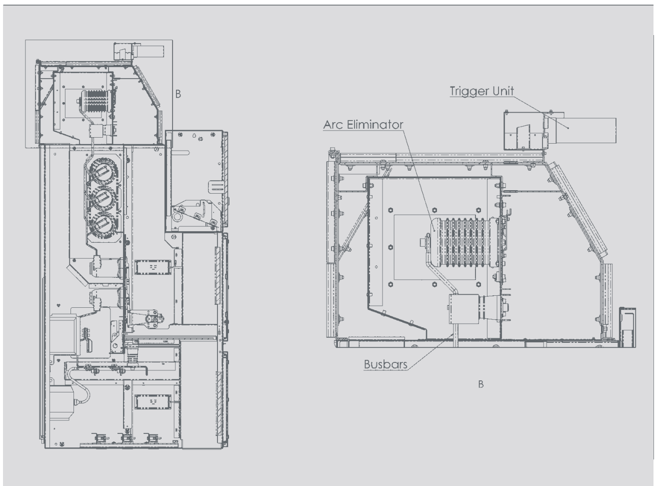
Footnote

1) The energy discharged in the arc is proportional to the square of the short-circuit current and the arc duration.

2a Arc Eliminator (AE) application on ABB's UniGear switchgear



2b Detailed drawing

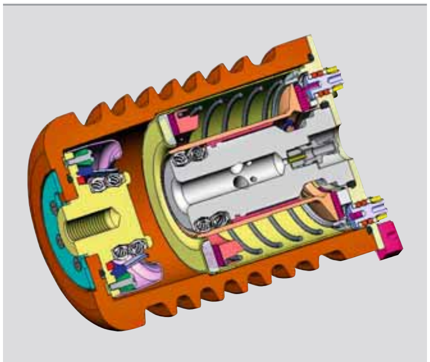


compartment, resulting in a temporary suspension of service and high repair costs.

Arc protection devices exist that can reduce the duration of the fault current feeding an internal arc, thereby significantly limiting the total electrical energy delivered to the fault. In fact, many ABB switchgears contain one of several arc protection systems available in the company's product portfolio, such as TVOC, REA, and FRD. Using either optical or pressure sensors, these electronic devices can detect the presence of an internal arc within a few milliseconds. However, the average intervention time required to eliminate the fault, taking into consideration the relay and circuit breaker time, is of the order 100 ms.

Current limiting devices can reduce both the magnitude and duration of the fault current. To do this, the device must be capable of operating within the first quarter of a cycle, thereby preventing the fault current from ever reaching the first peak of the asymmetrical waveform. An example of such a device is ABB's Is Limiter which has an extremely fast decoupling time of 1 ms. It can be installed in a dedicated switchgear unit, used in interconnections between systems, or in bus sections which are not adequately short-circuit proof when connected by a circuit-breaker. Even though it is costlier than other arc protection devices, the use of an Is Limiter in highly sensitive processes is justified especially when cost/benefit balance issues are considered.

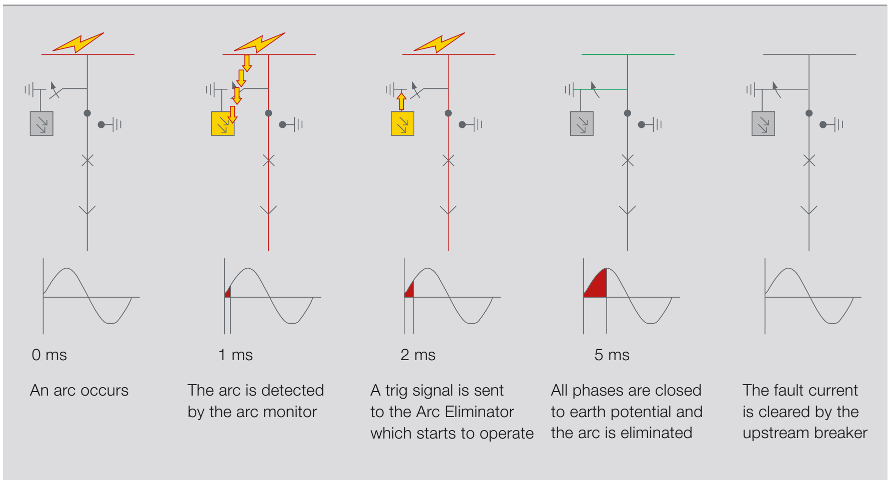
3 Arc Eliminator (AE) single-phase pole cross-section



ABB's Arc Eliminator (AE) can short circuit an arc within 5 ms. It can be used as a standalone device in existing switchgear plants and provides the operator with increased protection.

The Arc Eliminator (AE) merges the positive characteristics of the above fault limiting devices. It is considered the most optimal cost/benefit solution – one device can protect an entire busbar system – and is fast in that an arc is short-circuited to ground within 5 ms. A typical installation consists of an AE unit on each half busbar incomer for a system operated with open tie-breakers, and up to 10 panels are protected. Thermal damage, and consequently toxic arc gas release are drastically reduced to below one percent of what would be experienced in a one second internal arc test, making switchgear room pressure relief systems and exhaust conduits unnecessary. Even though the pressure rise is limited, it can still build up to a significant enough level before the AE can intervene, and switchgear relief systems, if present, will operate but with no release of hot or toxic arc gases.

4 Arc Eliminator – event sequence description



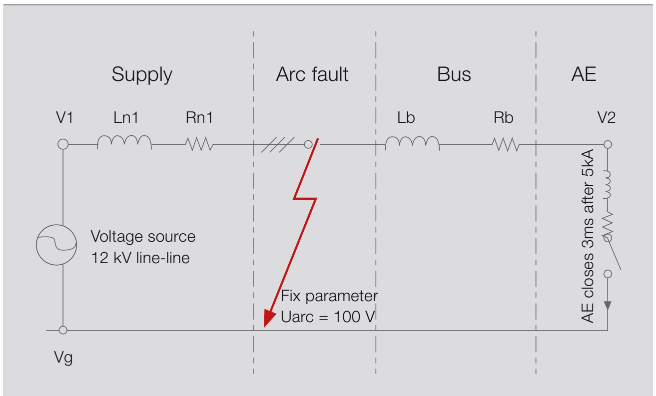
Initially developed and patented for ABB's AX1 AIS switchgear [3], the AE is now an integrated part of the company's UniGear AIS switchgear family **2**. The set-up is such that a metal box containing the AE is located on the busbar system. An arc is quickly detected by fiber-optics situated in every switchgear compartment. A UniGear switchgear equipped with the AE was successfully tested in the CESI labs in Italy, and the results are detailed in [4] and [5].

The AE can also be used as a standalone device in existing switchgear plants, functioning as an "active" protection system which is capable of detecting and extinguishing a fault in a few milliseconds (much like the ABS in a car). Additionally, the AE also acts like an airbag in that it provides the operator with increased protection.

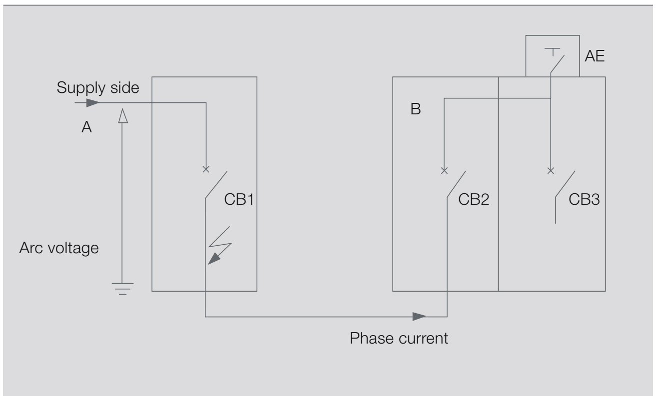
The Arc Eliminator (AE) device

Physically, the AE is a very fast-acting switch, and a single-phase pole cross-section is shown in **3**. Each AE switch pole is contained within an epoxy insulator. Light sensors provide the tripping signal through the AE Control Unit (ECU) in the event of an open arc fault in the switchgear high-voltage (HV) compartment. The moving contact, driven by the Thompson coil repulsion effect at high speed, bridges the SF_6 insulating distance to create a short-circuit between the copper ground plate and the HV terminal. This short-circuit takes less than 5 ms to form **4**. The arc requires a voltage of at least a 100 V in order to persist. However, after the contacts have closed, the voltage drops suddenly to

5 Simulated circuit to verify that the parallel impedance of the power circuit is low enough to ensure arc extinction



6a Power test set-up



a value that cannot sustain the arc. The insulation properties of SF_6 allow for a very compact design, and the same pole is used across the 12–24 kV range. The actuating energy for the switch contacts is electrically stored and the amount available for operation is continuously supervised [6], as are the power supply, trigger circuit and controller integrity.

A UniGear panel typically accommodates three physically separated high-voltage compartments (busbar, circuit breaker and cable). If an AE electronics module can handle up to six optical fibers plus one electrical input, then one AE is directly capable of protecting up to two panels. This number can be increased to 17 thanks to the development of a special electronic interface which connects one AE with up to five TVOC devices, each equipped with nine optical fibers. The tripping time is not affected by the presence of the TVOC.

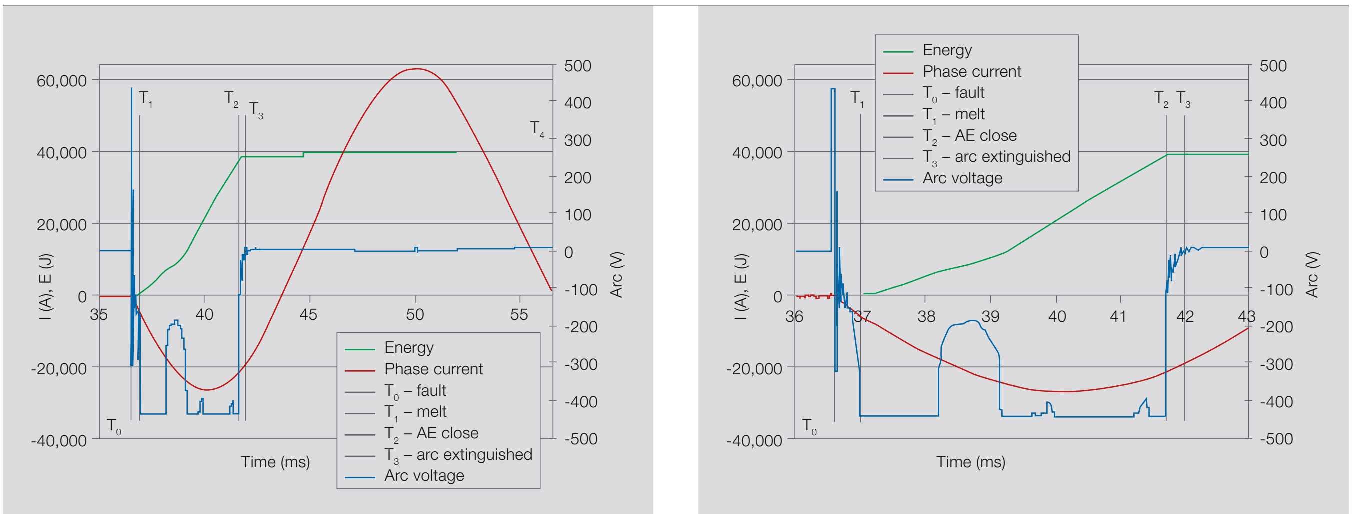
System operation

To verify the AE application in UniGear, the system operation and the maximum number of panels which can be protected by a single device must be evaluated. This depends on the impedance of the power circuit and the typical impedance of the UniGear switchgear busbar, Lb and Rb 5. The circuit in 5 is used to verify that the parallel impedance of the power circuit, ie, from the internal arc position to the AE short circuit to ground, is small as a function of the overall distribution system architecture, and therefore the voltage supplying the arc decreases with AE operation to extinguish the arc.

Preliminary results from simulation cases using between 4 and 10 panels have shown that current sharing between the fault (arc) and the AE is not a problem, even with a relatively large number of panels. It is also clear that the L/R ratio influences the current wave shape, and therefore the arc extinction capability. Larger L/R values mean the DC component decays at a slower rate, allowing the arc to live a little longer. The simulation results have been validated by power tests at the CESI labs [7], where a power cable was used to introduce a significant parallel impedance between the arc and the AE.

6a shows a test set-up in which an 31 kA internal arc starts in the CB1 panel and is transferred to the AE mounted on the CB3 panel. The corresponding graphs, using two different time scales, are shown in 6b. The quantities shown in these graphs are phase current (red), arc voltage (blue) and energy (green). At To, the supply

6b 31.5 kA arc transfer to the AE.



7 40 kA arc effects with AE intervention

voltage is closed on a three-phase fault which has been initiated by a low-section wire across the phases in the CB1 cable compartment. As the wire melts and an internal arc develops across the three phases, the voltage increases to several hundred volts (T1). At the same time, the current rises, flowing from the supply side to the arc location CB1. The energy input to the arc – which is accompanied with a flash of light – increases the air temperature and pressure. This flash of light triggers the ECU, immediately kick-starting the AE operation.

At T2, the AE grounds the three phases and closes, in parallel to the arc, a low impedance path causing the arc voltage to drop significantly. The current flowing in the arc diminishes and starts to flow out of CB1 through the cable connection into CB2, and from there to the AE. The entire process, from fault to detection to the AE closing sequence is completed within 5ms. By T3, the current has been fully transferred to the AE, the voltage drops to a few volts – depending on the parallel path length and impedance – and the current continues to flow until the upstream CB1 eventually cuts the supply. Because of its short-circuit ratings (31.5 kA, 3 s and 50 kA, 1 s), the AE can easily withstand the transferred current until this happens.

The T2–T3 transfer time, which can be anywhere between 0 and 2 ms, is influenced by the position of the AE with respect to the supply side, and the parallel impedance introduced by the new circuit when the AE closes. The 2 ms maximum value was evaluated during a 40 kA rms/100 kA peak internal arc test in CB1 using a 10 meter long cable, with a cross sectional area of 240 mm², connected to CB2.

The AE solution is simple, flexible, easy to install and very cost effective.

While the current, driven from the supply side, is not modified during the sequence, the AE operation strongly limits the voltage and therefore the energy input into the fault. In other words, when the AE kicks in, the energy input per period is substantially reduced to less than one percent of that during the free burning period (ie, from the current start to the closing of the AE) which lasted 5 ms, and this is illustrated by the "Energy" trace (in green) at T2 in 6b. Therefore all the effects normally associated with an internal arc are contained, resulting in no significant damage to the compartment.

In this test, the energy input to the arc during the 5 ms free burning period was about 40 kJ from phase one, and 94 kJ for all three phases. Had the internal arc continued for one second, the total energy released in the compartment would have been approximately 200 times that limited by the AE operation, ie, up to 2 MJ, thereby completely destroying all compartment inner components.

In any case, during the 5 ms free arc period, the switchgear must be able to withstand the forces associated with peak currents as well as the overpressure that causes relief flaps to open. Weak structural parts may be damaged as a result. In 7 this kind of damage is shown by traces of smoke around the phase conductor and a buckled aluminum bottom plate.

All in the name of safety

Operator safety must be a priority for a medium voltage equipment manufacturer and it can easily be achieved using ABB's AE. The AE solution is simple, flexible, easy to install and very cost effective. An AE service kit allows customers to install this solution in existing switchgears with only minor modifications, thereby increasing the safety level of existing equipment.

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[5] CESI, (2006). Test Report A6/004285.
[6] **Breder, H.** (2003). Frequently Asked Questions on the AX1 Arc Eliminator system.
[7] CESI, (2007). Test Report A7/015852.

Coming soon . . .

ABB Review Special Report
Process Automation Services & Capabilities

The ever-increasing competitiveness of the market and rising prices of energy and raw materials mean process plants are expected to meet the highest of standards in terms of quality, reliability and cost-effectiveness. With wastage and unplanned downtime becoming increasingly unacceptable, plants must not only achieve optimal operating conditions, but also maintain them permanently.

The scheduling of maintenance, for example, requires advanced understanding of the equipment in question. Only by making full use of this knowledge can costly downtime and even more costly failures both be minimized.

ABB is not only the world's largest supplier of process control systems, but also is increasingly involved in supporting customers in maintaining and developing this equipment. The forthcoming *ABB Review Special Report Process Automation Services & Capabilities* highlights some of the company's contributions in this area.

Surviving a short-circuit

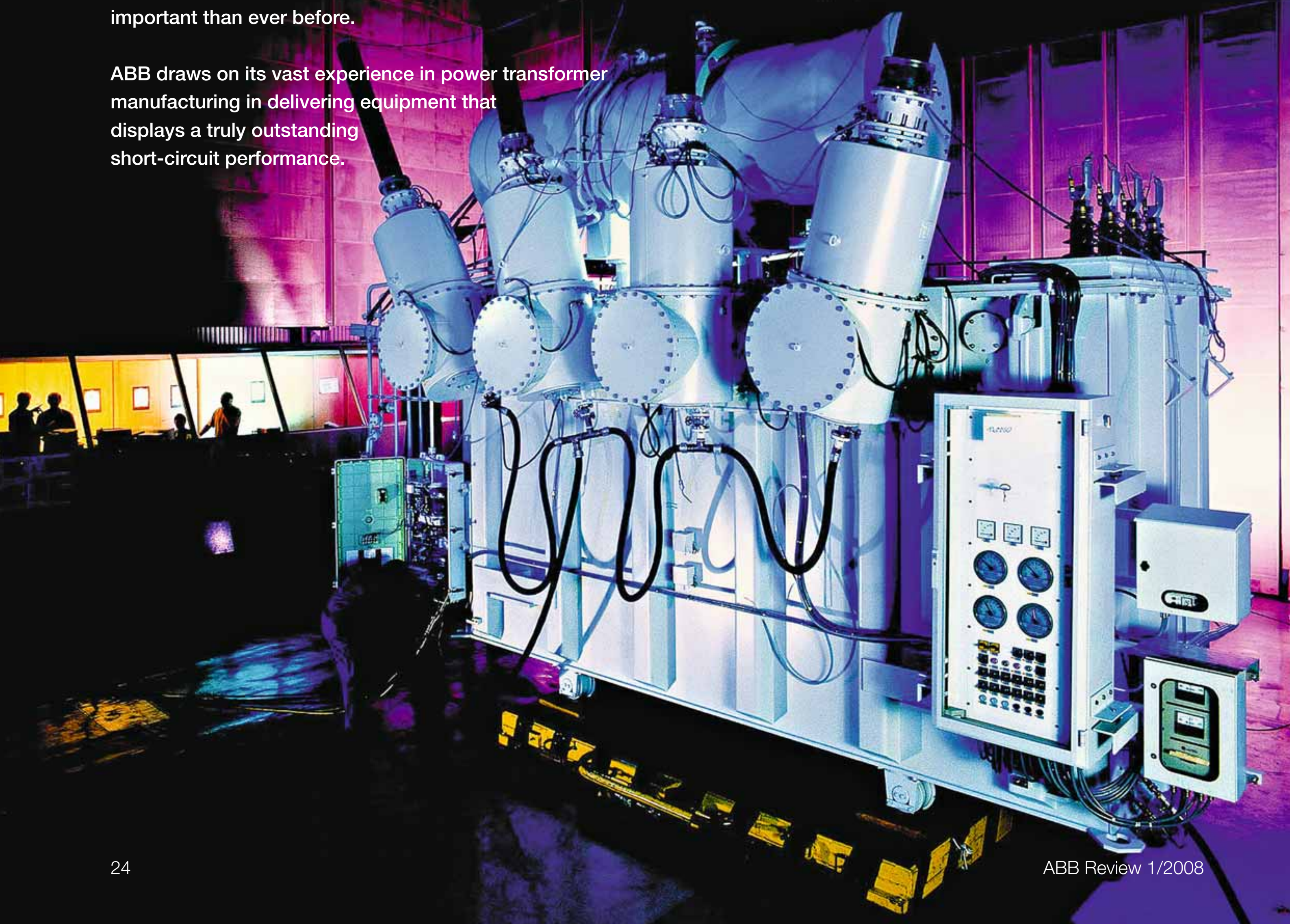
Short-circuit withstand capability of power transformers

Thomas Fogelberg

The power transformer is a vital component in the transmission of electric power. Thanks to the many years of accumulated knowledge, experience and sophisticated development in production and testing processes, the transformer is now a highly efficient piece of apparatus with an outstanding reliability.

Transformers, however, are not the only components to have experienced changes. The rapidly evolving electricity market is causing networks to be operated closer to their limits. At the same time, the booming demand for new transformers combined with high material prices is putting pressure on manufacturers and their suppliers. All these aspects combine to make assuring the robustness of transformers more important than ever before.

ABB draws on its vast experience in power transformer manufacturing in delivering equipment that displays a truly outstanding short-circuit performance.



As power ratings and transmission voltages have increased, the thermal and mechanical aspects of transformers have become more pronounced, both in terms of local over-heating control and in the need for withstanding electrodynamic forces originated by fault events occurring in electrical systems. ABB's transformers are today handling 800 kV, the highest commercial transmission voltages presently in use. They are also handling three-phase ratings of 1500 to 2000 MVA in system intertie applications and up to 1200 MVA in generator step-up applications.

Background

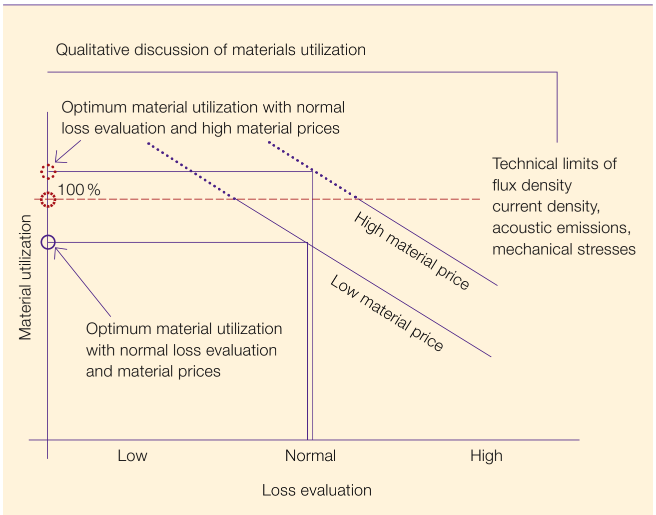
The demand of transformers is now booming in a way similar to after the Second World War. At that time, European and American markets were served by domestic suppliers who invested to full capacity to meet the needs of state-controlled utilities and power companies. Installations of 400 kV to 800 kV AC were implemented. It was also a time when numerous IEC and ANSI international standards were laid down.

The first signals of a shift in demand appeared in the early 1980s. By the end of this decade, the electrical system industry has gone through its biggest change since the inventions of Edison and Westinghouse.

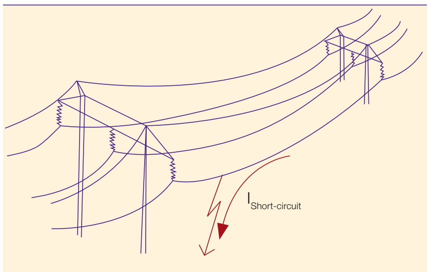
The last 25 years have been characterized by a huge global consolidation on both the supply and user side of electrical equipment. A fully domestic business has been transformed to a fully global one, with consequences in both commercial and procurement matters. The procurement side has additionally had to deal with the markets for raw materials, many of which are no longer in their traditional balance.

Changes to the grids were motivated by rational reasons for opening up markets to enable trading and regional interconnections. Political stakeholders wished to enable increased competition. As a result, many former governmental bodies have been transformed to profit-making companies. Production, transmission and distribution were broken up into separate entities, with the role of transmission becoming weaker and less clear as a result. It has especially become more difficult to obtain a collective responsibility. Fluctuations in prices are considered the concern of end-customers and long-term commitment in infrastructure has shifted to a shorter-term horizon.

1 The choice of materials involves a trade-off between material losses and price



2 Failures caused by short-circuits are still a major cause of transformer outages



For the transformer market in particular, the most significant changes of recent years are caused by the huge demand for electrical energy in regions such as Asia, the Middle East and South America. Additionally, the so-called "old world" has needed to re-invest, as the age of its transformer fleet reaches 40 to 50 years. These developments are additionally boosted by environmental concerns.

Furthermore, the increasing demand for transformers is pushing manufacturing facilities and their material suppliers to the limits of their capacity, leading to extended delivery times.

Meanwhile, growth in grid utilization is outstripping new investment, leading to individual components being operated closer to their limits.

Testing

The testing of new transformers is the utmost demonstration of their quality. Today's designs, marked by high material prices and often low loss evaluations, are seeing materials being pushed closer to their limits and exposed to greater stresses than ever before **1**.

The acceptance testing concerning dielectric aspects is well covered by the international standards that have been developed over the years. The proving of thermal and mechanical integrity of new large GSU (generator step-up) and intertie transformers is still, however, a field where design and production weaknesses can pass without being detected.

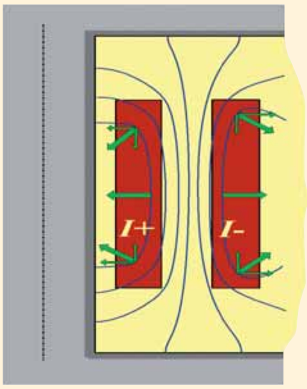
This article mainly addresses how ABB's design, production, supply chain and testing philosophy verifies mechanical aspects of reliable large power transformers – in other words, their ability to pass a short-circuit test.

Reliability

Modern power systems are complex arrangements with a high number of individual pieces of apparatus. To ensure reliable operation, it is of utmost importance that key elements such as large power transformer have a high degree of availability, thus minimizing the outages of individual components or whole blocks of power generation.

The ability to withstand a short circuit is recognized as an essential characteristic of power transformers. IEC and IEEE Standards, as well as other

3 Electromagnetic forces tend to minimize the density of magnetic energy



Factbox Attributes of power transformers manufactured by ABB

A short-circuit safe transformer is characterized by
- Mechanical sound design and technology
- Based on fundamental mechanics
- Verified by many short-circuit tests
- Rigid core clamping structure for short-circuit strength and transport
- Accurate manufacturing guided by strict tolerances and quality systems
- Rigid winding mandrels
- Verified drying and pressing procedures
- Rigid low-voltage winding design and clamping

Recommendations
Which units are worth being considered for short-circuit testing?

- Important generator step-up transformers and auxiliary units in power plants
- Key feeding transformers at power plant sub-stations or huge load centers
- Strategic intertie transformers three-winding system transformers (tertiary), auto-transformers
- Transformers with axial split winding connections
- Series of transformers, one to be taken out
- Always track feeding transformers
- Transformers connected to networks known for many faults and high fault currents

All power transformers designs/contracts to be checked by design reviews to IEC 60076 – Part 5 (2006-02)

national standards hence specify that power transformers have to be short-circuit proof and lay out how this should be verified. Unfortunately, however, there is extensive evidence that the matter is not as simple as the standards would suggest. The failures caused by short circuits 2 are still a major cause of transformer outages – though failure rates vary widely in different countries and systems, depending on various circumstances, network characteristics and the equipment installed.

Nowadays fast developing regions, with steeply rising demand for electric power, are adding more and more generating capacity and interconnections to their systems. In addition to this the western world is characterized by:
- Expanding cross-border electricity trade (bringing network operations close to their physical limits)
- Development of wind generation (which is often integrated into the grid without taking into account available network capacities)
- Changing load flows
- Ageing network components
- Changed network operating conditions

These factors lead to old and new transformers being exposed to severe short-circuit requirements.

ABB has succeeded in building transformers with an outstanding reliability record. This is a result of dedicated development work, long time experience in building transformers for the most demanding service conditions and meticulous follow-up of incidents taking place in tests and operation.

Ten years ago, ABB launched the business concept, TrafoStar™. This integrates engineering tools, manufacturing accuracy, major suppliers with common material specifications, testing and quality management system. This concept is now used for large power transformers in 14 plants in all global regions. Since the inception of TrafoStar™, 10,000 power transformers have been produced according to this concept; of these, 2,000 units are very large GSUs and intertie transformers. More than 1,500 power transformers of more than 60 MVA rating are produced every year.

Design considerations
How will all those changes affect today's design and future reliability and availability? In view of rising demand, many new suppliers will be entering the market, with distribution-side manufacturers also moving into the power transformer sector. At the same time, the large increase in material prices, combined with traditional low loss evaluations, will drive stresses upwards as margins are reduced.

The mechanical rigidity of a transformer will become the most vital performance factor for the future. There are three reasons for this:
- Withstand to short circuit stresses
- Seismic requirements
- Transport handling

The short-circuit force gives rise to mechanical forces that can reach hundred of tons in milliseconds. The current peaks and the corresponding forces depend on many factors. In high-voltage systems, the most probable type of short circuit is a single-line-to-earth flashover, normally due to environmental conditions such as a lightning strike on the line, equipment failure at the station, pollution of insulation strings, and similar causes. Sometimes, short-circuit faults will develop into other more extensive faults, such as single-phase-to-earth faults developing into a double-phase-to-earth and eventually three-phase faults. The relative severity of the different types of fault depends on the characteristics of the system. On the other hand there are factors such as arc resistances and earth network impedances that have some compensatory effects. The severity of a short circuit and the peak current and forces depends to a considerable extent on the condition of the installation, and in particular on the short-circuit impedance value of the transformer and the short-circuit apparent power of the system(s).

The fault configuration that normally gives the highest through-currents in any winding of the transformer is the symmetrical three-phase fault. Hence, it is meaningful to use this fault mode as a basic design criterion for the transformer.

In dealing with short-circuit events in power transformers, the first step is to evaluate any very high fault currents that will affect the windings in connection with the various types of faults the unit is likely to experience in service.

When determining the magnitude of the currents, circuit analysis and theory of symmetrical components are used. The calculations are performed by means of automated programs, since the system and the transformer characteristics constitute the input data.

Force calculations per failure mode

Electromagnetic forces tend to deform the windings so as to minimize the magnetic energy density stored in their volume. For a two-winding transformer example, this means that an inner winding will tend to reduce its radius and an outer winding to increase its radius. In axial directions, the windings get compressed to reduce their height 3.

Forces and relating withstand criteria can be split into two components:

- Radial forces
- Axial forces

The failure modes for radial forces include:

- Buckling of inner windings 4a
- Stretching of outer windings
- Spiraling of end turns in helical windings 4b

The failure modes for axial forces include:

- Mechanical collapse of yoke insulation, press rings and press plates, and core clamps
- Conductor tilting
- Conductor axial bending between spacers
- Possible initial dielectric failures inside windings, followed by mechanical collapse

The axial forces are calculated with programs based on finite element method (FEM) that fully take into account axial displacements caused by workshop tolerances and pitch of helical type windings. Windings are dimensioned for maximum compression forces, where dynamic effects are embedded.

An important feature of ABB's short circuit technology is that inner windings subject to radial compression are designed to be completely "self-supporting" as regards any collapse by "free buckling". For this reason, any – often questionable – contribution to stability granted by radial supports from the core to the windings or from one winding to another is deliberately ignored in any ABB transformer designs.[1)] This means that the mechanical stability of the winding is determined by the hardness of the copper (yield point) and conductor geometry. Spiraling in helical type windings is avoided by strictly limiting the forces that can occur, or by changing the type of winding. Also the dynamic response from the winding is considered.

Designing power transformers is an iteration and interaction process that seeks the optimal solution from the point of view of:

- Masses and losses
- Sound level
- Short-circuit strength
- Winding temperatures, hot spots and cooling equipment
- Dielectric strength between windings and inside windings

ABB's designers are supported by the world's most advanced set of design and verification programs for power transformers. These interactive appli-

Footnote

1) The reliance on radial supports can compromise the mechanical stability of the windings due to relaxation of the supports under load and over time

4 Examples of deformations caused to windings by extreme forces:

a Buckling: Collapse of the cylindrical winding shell

b Spiraling: Tangential shift of the end turns in helical-type windings

5 Transformer manufacturing requires a high degree of accuracy

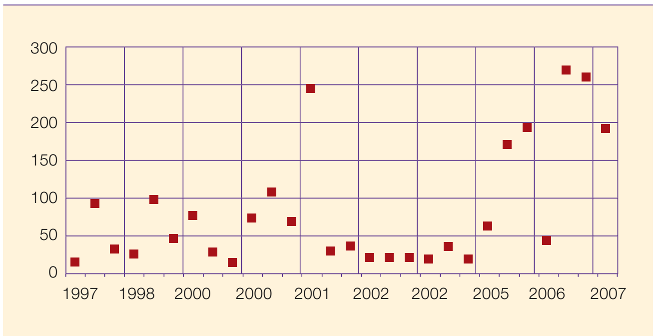
cations are used today in 14 power transformer plants.

Manufacturing and accuracy

Ampere-turn balancing between the windings is a prerequisite to avoid excessive axial forces on the windings.

This is achieved through strict manufacturing tolerances for windings 5.

7 Rated power (MVA) of SC tested TrafoStar™ transformers



Since the windings can be regarded as springs built of about 20 percent cellulose, the correct compacting when exposed to moisture and temperatures is important in obtaining the exact length and spring constant for long-time service. Well defined processes in the winding shop and active part assembly are necessary. The final pressure setting after the vapor-phase process is used to bring the windings under pressure for their life time.

The most important criteria are that all windings need a given pressure to avoid any displacements between the coils. The different cellulose-based components are manufactured and treated from raw material entirely in ABB's own pressboard machines and kit-centers around the world. This secures a common method of producing all these key elements with significant influence on the winding's dynamic strength 6.

6 ABB's common method of manufacturing secures a common method of producing all key elements. This has significant influence on the winding dynamic strength.

A short-circuit force gives rise to mechanical forces that can reach hundred of tons in milliseconds.

Short-circuit strength verification

The new IEC Standard 60076-5 (2006-2) provides two options for verifying the transformer's ability to withstand the dynamic effects of a short-circuit. These are:

a) A full short-circuit test performed at a certified lab or
b) A theoretical evaluation of the ability to withstand the dynamic effects of short-circuit events based on the manufacturer's design rules and construction experience, in line with the new IEC guidelines

8 Due to the high investments involved, power transformer short-circuit testing can only be performed in few places in the world. This is KEMA in the Netherlands.

On account of the high investment costs in test equipment, such tests are possible in only a handful of locations in the world. The test requires power capacities in the range of a large power grid together with sophisticated control and measuring equipment. One such facility is KEMA in the Netherlands, where a number of short circuit tests were carried out on behalf of ABB 7.

More than 140 ABB power transformers of different designs have passed short-circuit tests, including around 30 that were built after 1996 according to TrafoStar technology 8.

In CIGRE and at other technical conferences, KEMA reports are showing test failures in around 30 to 40 percent of the performed SC tests on power transformers. ABB's own test record over the last 11 years has been three failures out of 28 tests. When the ABB tests are removed from the overall statistics, other manufacturers are showing much higher short-circuit test failure rates. This highlights the extreme challenge of building fully short-circuit safe transformers in the world today.

The new IEC Standard also allows for a design verification where the manufacturer shows its calculated stresses and compares it with its own rules manifested by several short-circuit tests. To comply with this Standard, stresses shall not exceed the manufacturer's maximum allowable stresses or 0.8 of the critical stress value identified by the manufacturer. The stress values must furthermore comply with the corresponding maximum ones given for guidance in the new IEC Standard 60076-5.

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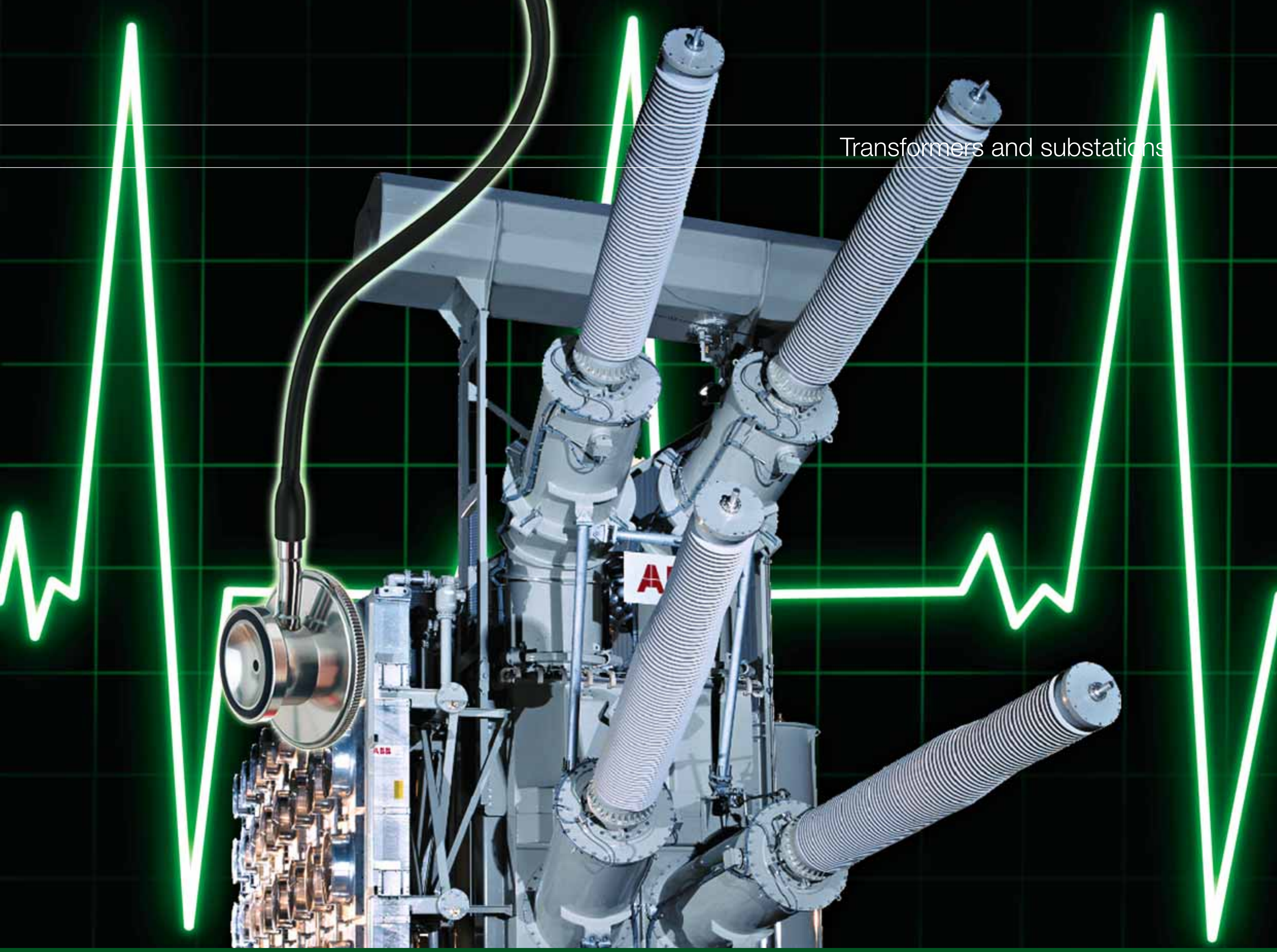


Transformer challenges

Condition monitoring is becoming a strategic tool for utilities

Lars Pettersson, Lena Melzer, Claes Bengtsson, Nicolaie Fantana

As crucial components in electrical grids, transformers are built to the highest standards of precision and quality and designed for a long lifetime. As the average age of these transformers is in the range of 30 to 40 years in many countries, the probability of malfunction is on the rise.

This situation is accentuated by the trend to operate transformers closer to their performance limits, adding to their vulnerability if adequate countermeasures are not taken.

The replacement of a failed transformer is not a matter that can be completed within days. This makes it all the more important to minimize the probability of such an event. This article explores how ABB can help utilities gain a greater insight into the health of ageing transformers and so achieve a better management of their assets.

Transformers and substations

To optimize their replacement and refurbishment strategies, utilities need to evaluate the condition of their transformer fleet [1,2]. The spectrum of technical measures for a utility to manage a population of transformers covers three areas:
- Detection/prevention of incipient failures by means of supervision and monitoring
- Identification of malfunction/fault by diagnostic evaluation and
- Strategic planning for repair, replacement, etc. by condition assessment and fleet screening.

Modern monitoring systems, such as ABB's TEC (Transformer Electronic Control), not only aim to detect faults but also provide data collection functionality for condition assessment.

Besides using direct measurements, the diagnostic evaluation relies on theoretical considerations drawing on ABB's in-depth knowledge of transformers and on modern design tools. Application examples are advanced frequency response analysis, dielectric response measurements and calculations of short-circuit strength and overloading capability.

The condition assessment and fleet screening functions support strategic decisions related to both single units and larger populations. The data used are drawn from design, operational history and diagnostic measurements and evaluation.

ABB has the expertise to assist transformer owners in all these areas but can also help with various advanced on-site activities such as repairs or upgrading [3,4]. In order to illustrate the practical application of ABB's transformer condition assessment, this article presents three cases. They cover:
- Strategic planning or fleet screening
- Transformer life extension
- Supervision of a suspect unit

Evaluation for strategic planning

The objective of strategic evaluation of a population is to identify the most vulnerable units so that maintenance or replacement activities for those units can be prioritized. For the strategic evaluation two different approaches can be taken:
- Statistical analysis, mostly with transformer age as the major independent variable
- A unit oriented method to determine the condition or withstand strength of each individual unit

While the statistical analysis often serves as a useful first step, the individual and unit-oriented approach is required in most cases.

Fleet screening: influential factor method

This evaluation involved 49 net transformers, rated between 40 and 100 MVA. Various influential factors having a bearing on the life expectancy of the transformers were identified. Each transformer in the population was then evaluated and assigned a relative score for each of the factors.

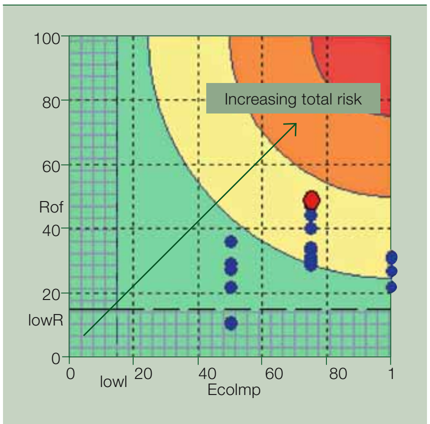
The score value is a number between 0 and 100, with 100 indicating the worst and most severe condition for the factor being looked at.

Because some influencing factors are more critical than others, a weighting value was additionally assigned to each influential factor.

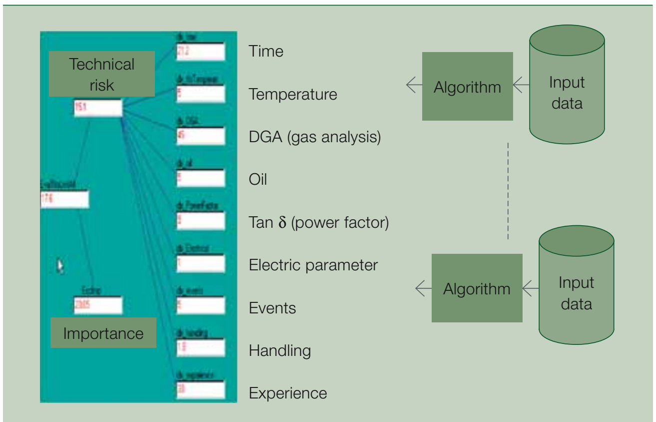
The overall indication for a potential technical risk for a particular transformer was then determined by combining the individual scores – either as a weighted sum or by using the maximum value of the individual scores.

The influential factor evaluation method used here is illustrated in 1 and is based on accessible parameters. Some of these pertained to a general historic

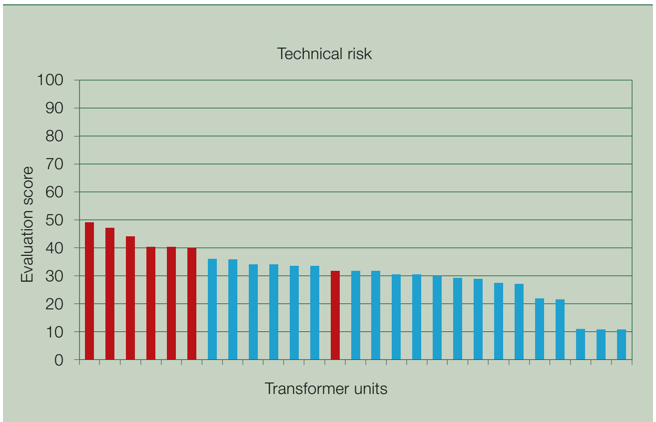
3 Total result of the ranking. The device marked in red presents the highest risk.
Rof: technical risk potential
EcoImp: economic relevance



1 Transformer screening uses algorithms based on data that are easily determined and defined. These data are expressed as scores between 0 and 100.



2 Technical risk indication based on the weighted value approach. The devices shown in red are at the highest risk.



degradation, others are directed towards thermal wear, possible extraordinary events, repair status and experience. Finally, there is a group of data related to the actual condition of the transformer determined by DGA (dissolved gas analysis) and oil analysis.

For the 49 transformers investigated, data were available on rating, age, load, ambient temperature and DGA results. For some units, information also existed on design and on extraordinary events. Oil analyses were available for 27 units. Hence, two rankings were performed – one ranking involved the latter 27 units and the other included all 49 units without considering the oil analyses.

The results of the ranking of the technical risk indication of the 27 units using the weighted score approach is presented in 2. The six transformers to the left are at highest risk.

If the analysis is supplemented with an evaluation based on the maximum parameter value instead of the weighted value, one more unit (also marked red in 2) is added to the "high potential risk" group.

The high risk group is characterized essentially by higher degradation of oil and paper insulation. Age alone, however, did not determine the ranking order.

The overall exposure for a utility does not only consist of the technical risk but it also depends on the economic consequence of a possible fault, eg, cost of non-delivered energy, cost of repair. Hence, an economic parameter referring to this consequence is defined with a relative value between 0–100, provided directly by the utility.

A combined view of technical risk potential (Rof) and economic relevance (EcoImp) is shown in 3.

Although a significant ranking was obtained, the DGA information indicated that the risk of an imminent failure was low in this population. However, for some of the transformers, oil treatment was recommended and a deeper analysis of the ageing status was later performed on the unit with the highest assessed risk.

The condition assessment and fleet screening functions support strategic decisions related to both single units and larger populations.

As an alternative to the view in 3, a risk index can be defined as the normalized product of the technical risk and the economical parameter. The risk index can be seen as a measure of the expected consequential cost of a failure, a value that in some sense is related to an insurance risk premium.

Fleet screening: rule-based approach

In a more detailed and structured evaluation, the aim is to determine either the condition of the transformer, the condition of its sub-components or its withstand strength against specific external stresses. The various sub-components or stresses such as thermal, mechanical or electrical stress as well as the loadability are analyzed individually. A separate evaluation score (or potential risk of failure) is associated with each of these sub-components/stresses. In an overall evaluation the sub-scores may be combined into a total score 4.

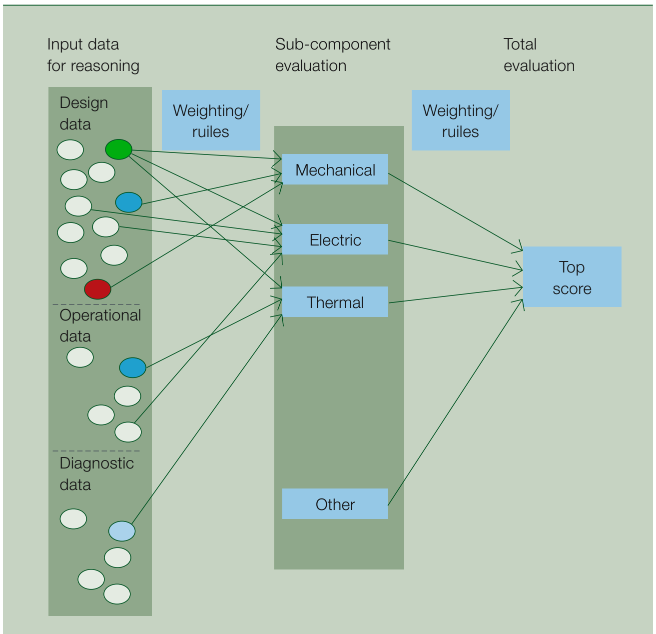
The method of deducing an evaluation score for a sub-component may be based either on a combination of influential factors, addressing only that particular stress/condition, or it may be a rule-based reasoning model reflecting deeper transformer knowledge. In a structured evaluation, a parameter value may enter into the evaluation of several sub-components. For instance, time-in-operation not only affects the ageing of paper but also the relaxation of the clamping force in windings. The interpretation of DGA results is relevant in both the electrical evaluation and in the thermal evaluation.

In one of the case studies discussed here, thirteen 220 kV substation transformers, manufactured between 1969 and 1998, were investigated. Their ratings varied between 63 and 315 MVA, with one 400 kV/500 MVA unit also being included. Some units were free-breathing while others were sealed with a rubber diaphragm. All units but one had an on -load tap changer and all but one had a short-circuit impedance between 10 and 12 percent, with the exception of unit number 3 which had an impedance of 22 percent.

The following subcomponents were evaluated in this assessment:

- Short-circuit strength (determined from buckling and tilting strengths)
- Electrical risk (deduced from design parameters, oil analysis and DGA results)
- Thermal ageing of paper
- Overall heating of insulation (deduced from oil and DGA analyses)
- Core heating
- Loadability of the transformers (short time and long time emergency loading capability)

4 The structured model used to evaluate a transformer's risk



Some of the aspects were evaluated using rules while other parameter scores were determined from influential factors. The results of the ranking with respect to short-circuit strength and loadability are shown in 5 sorted by year of manufacture.

The evaluation shows that
- Both types of evaluation categorize the transformers into 4–5 subgroups
- Units 2 and 5 have the highest risk at an external short-circuit event but are less stressed at overloading
- Unit 3 (with the highest impedance) has the best short circuit strength but the lowest loadability
- Comparing the units with 10 to 12 percent impedance shows that the newer ones have a better short-circuit strength than the older ones
- no clear time dependence in the loadability is visible

The other sub-parameters were evaluated in a similar way.

In the case presented, the working condition of all evaluated transformers was good. However, if exposed to special extraordinary events (short-circuits or overloads) transformer units 2, 3 and 5 could be in danger.

ABB has performed several evaluations, both with the influential parameter method and the structured rule-based approach in Europe and in USA [5,6,7,8].

Life extension study

A life extension investigation involves an evaluation of the present condition of the transformer and an estimation of the "remaining" life of the insulation under given assumptions about the future service.

Fleet screening can be done with rule based or influential factor methods.

The present condition is normally determined from an assessment of the immediate risk of failure, determined by the DGA and oil analysis, and an estimation of the "consumed" life of the insulation. Information about previous events that may have stressed the transformer is also taken into account. Electrical and mechanical risks have to be evaluated as well.

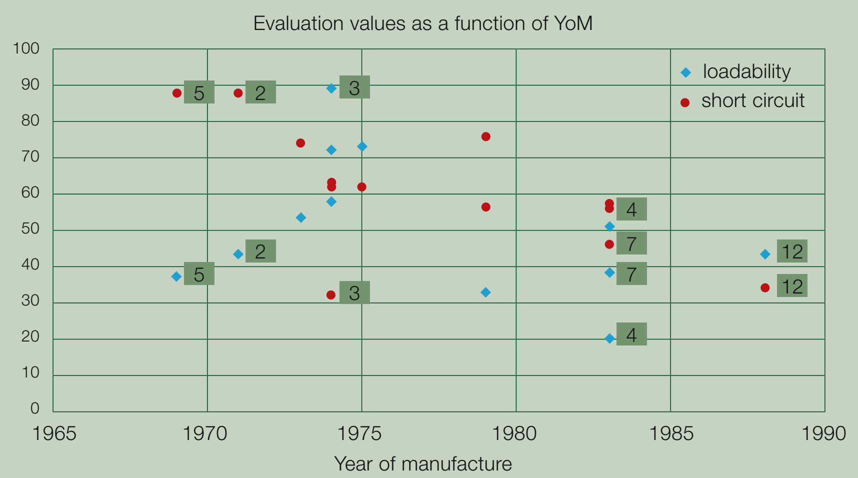
In the case presented here, the transformer was a generator step-up (GSU) transformer manufactured in 1979. It was free breathing and oil-forced water-forced (OFWF) cooled. The transformer had insulated bus ducts on the low voltage side. The average load was 78 percent of rated load but during the years it had varied between 35 percent and 100 percent.

The transformer had been exposed to some minor events – causing gas alarms – and one, more severe, extraordinary event: a one-phase earth fault on the high voltage side producing high currents through the transformer.

The results of this investigation were as follows:
- Oil and DGA analyses showed a low immediate risk of failure.
- Estimation of the ageing of the paper insulation at hot spot indicated a DP – value around 350 (see Factbox).
- Ageing of oil was low but it was expected that the inhibitor would be expelled in another seven or eight years with the same future thermal stress. Hence, a recommendation was given to treat the oil, preferably using oil reclaiming, within five years.
- The short-circuit strength of the transformer did not fulfil the present ABB standards, especially regarding the buckling strength of the low voltage winding. The calculations showed that an external single phase high voltage to earth fault could stress the transformer to the limit or beyond.

In conclusion, the short circuit strength was limited but the transformer was otherwise in acceptable condition. Due to the limited short circuit capability the transformer was replaced.

5 Ranking of the units as a function of year of manufacture (YoM). The numbers in the boxes refer to individual transformers. A higher, ordinate score means a higher relative risk.



Factbox The DP

The DP (degree of polymerization) is the average number of glucose monomers of the cellulose molecule. It is related to the mechanical strength of the insulation paper and its decline is hence a measure of the paper degradation. The DP value at the winding hot spot location can be estimated if the temperature, deduced from the as-designed temperature profile and service data, is known together with data from oil analysis and DGA.

Evaluation of a suspect unit

This case concerns a medium-sized 50 MVA GSU transformer, OFWF-cooled and free-breathing, manufactured 1962 and located indoors.

In the DGA evaluation acetylene (C_2H_2) had been detected, indicating a possible internal fault.

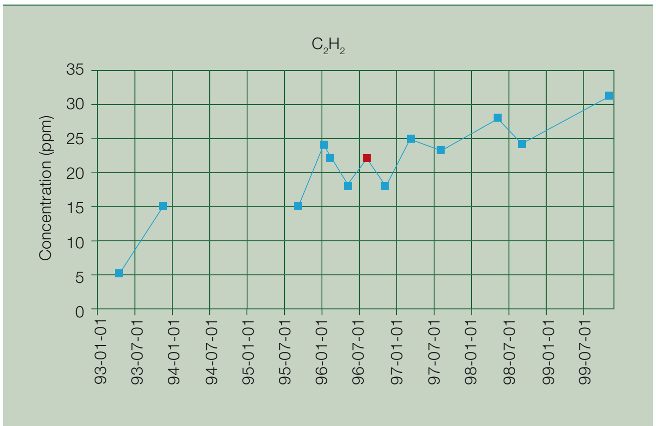
The temporal development of acetylene, showing small incremental jumps, is shown in 6. The red point in the graph indicates the start of the diagnostic evaluation.

The levels of the other hydrocarbons were low and practically constant, the carbon oxides indicated a somewhat aged transformer but their concentrations were not exceedingly high. Finally, the hydrogen level was low and constant.

Life time extension, upgrading and risk reduction have an immediate effect on the bottom line of the utility business.

Increasing acetylene concentration is an indication of electric discharges in the oil, supported by the overall DGA gas pattern showing almost no cellulose content. Discharges of this type are often due to a local charging/discharging effect of a metallic piece in the transformer.

6 Evolution of acetylene (C_2H_2) found in the main tank of a monitored transformer



To find the root cause of these possible discharges, the design of the transformer was scrutinized in detail, a more complete oil analysis was performed and acoustic and electric PD (partial discharge) measurements were performed on-site.

The PD measurements showed strong electric discharge pulses. The discharge pattern resembled the pattern of streamer discharges propagating in oil. The acoustic measurements found two acoustic sources, but no definite localization of the source could be made.

Possible sources of these discharges were a shield on floating potential located around a LV-lead or PDs between core and tank. As these did not impose an immediate danger to the transformer, it was recommended to keep it in service with frequent DGA analysis. Based on this recommendation the transformer was kept in service for another couple of years. A subsequent analysis of the transformer after it was taken out of service confirmed the source of discharges.

A valuable service for utilities

The cases presented demonstrate how a careful condition assessment, on the fast track or very detailed, helps utilities to manage the ageing fleet of transformers. Other important aspects such as the possibility of upgrading transformers have been addressed in condition evaluation studies as well. Life time extension, upgrading and risk reduction have an immediate effect on the bottom line of the utility business and preventive monitoring pays off immediately.

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Substation evolution

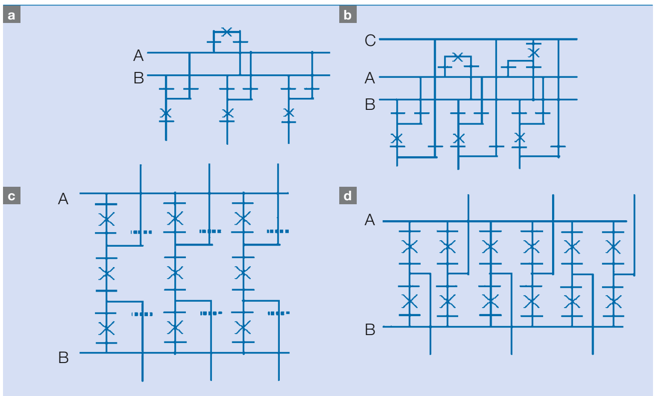
Substation design in the 1900s and modern substations today

Hans-Erik Olovsson, Sven-Anders Lejdeby

A hundred years is nothing compared with the length of time man has been roaming the earth. In terms of technology, however, it is an eternity. When ABB manufactured its first substation about 100 years ago, who would have guessed what a typical substation would be like today. Back then, the circuit breakers used were bulky and complicated, requiring constant supervision and frequent maintenance. Much of the 20th century focused on developing new technologies that would increase capacity, availability and limit maintenance, as well as addressing the issues of size, speed and automation. Some of these developments and innovations led to the launch in the 1960s of gas insulated switchgear (GIS). These smaller and compact switchgears reduced the dimensions of a conventional air insulated substation by almost 90 percent! In the 1970s, conventional electromechanical protection was replaced by static (operational amplifiers) protection, and further innovations have resulted in the current numerical control and protection systems, incorporating multiple functions and tasks, that communicate with other systems via digital technology.

For some time utilities have been able to remotely operate and control substations without the need for on-site personnel. Pre-engineered, pre-fabricated and modularized substations are available in various AIS and GIS configurations, enabling short delivery times and a high quality of installation.

1 Different types of single-line configurations: double busbar a, double plus transfer busbar b, 1½-breaker c and 2-breaker d. a and b focus on maintenance, whereas c and d cover both maintenance and fault aspects.



When the building of electricity systems started in earnest some 100 years ago, the network wasn't particularly reliable. The circuit breakers were mechanically and electrically very complicated and required frequent maintenance. Outages due to maintenance were the norm rather than the exception. The invention of the disconnector switch certainly helped to increase the availability of these electrical networks. The single-line configurations used were such as to surround the circuit breakers by many disconnector switches so that adjacent parts of the switchgear were kept in service while maintenance was carried out on the breakers. These ideas led to the double busbar and double plus transfer busbar schemes 1a and 1b. In addition to maintenance considerations, single-line configurations were chosen to limit the consequences of primary faults in the power system (eg, if the ordinary circuit breaker failed to open on a primary fault on an outgoing object, or if a fault occurred on the busbar). For the configurations shown in 1a and 1b, these types of faults will lead to the loss of all objects connected to the busbar. To limit these consequences while still retaining the maintenance aspects, 1½-breaker and 2-breaker single-line configurations, 1c and 1d, were introduced.

Today's breakers require less maintenance than their predecessors. In fact, ABB's SF_6 circuit breakers have a maintenance interval (where the primary components need to be taken out of service) of 15 years. Open air disconnector switches on the other hand still retain a maintenance interval of about four to five years in areas where there is little or no pollution. Substantially more frequent maintenance is required if the switch is located in areas with natural (ie, sand or salt) or industrial pollution.

Even though disconnecting switches – or rather a disconnecting function – are needed, their maintenance requirements are simply not practical, let alone economical. A number of innovative switchgear concepts for Air Insulated Substations (AIS) have effectively made the traditional open-air disconnecting switch redundant 2. The disconnecting function has either been built onto or integrated into the breaker. This not only increases the availability of the substation, but it helps to reduce its footprint by about 50 percent. The impact of going from a traditional solution, for example a 1½-breaker solution for a 400 kV AIS with circuit breakers and disconnecting switches, to a solution using Combined (disconnecting circuit breaker) is shown in 3. The advantages of a reduced footprint include lower costs for land acquisition and preparation, the retrofitting of existing substations is easier, and the environmental impact, because of less material and therefore pollution, is considerably reduced.

Instrument transformers today

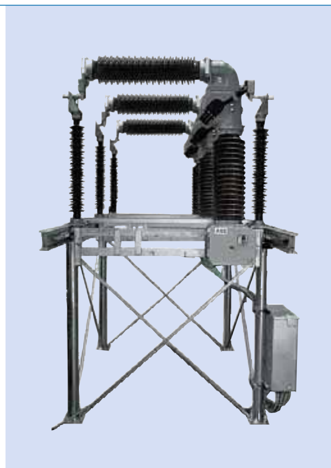
Instrument transformers pass on information about the primary current and voltages to the secondary equipment (protection, control and metering). Historically these transformers were large apparatuses composed of insulation materials, copper and iron. They were also used to power the electromechanical secondary equipment. Nowadays, the numerical type of secondary equipment gets its operating power from a separate power supply (ie, battery). In addition – thanks to

2 ABB Innovative Switchgear Modules with the disconnecting function either built on or integrated into the circuit breaker

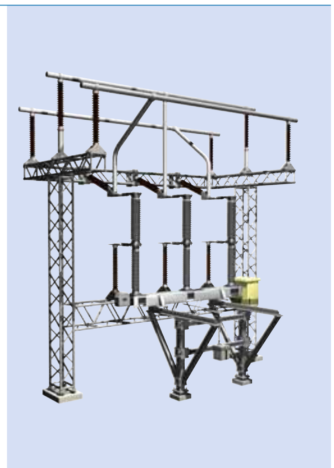
a Combined

b PASS

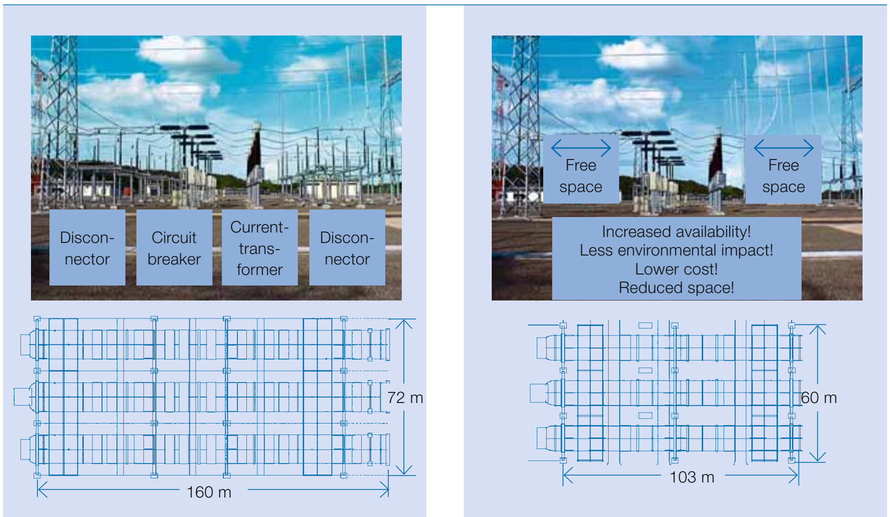
c Compass



d Compact



3 The impact of changing from 400 kV traditional circuit breakers and disconnecting switches (left) to a Combined (disconnecting circuit breaker) solution.
Notice the reduction in footprint size



the emergence of fiber-optic technology – the old large instrument transformers can be replaced by fibre-optic sensors that give information about primary currents and voltages. These values are transformed into digital fiber-optic signals, which are fed to the secondary equipment. Replacing traditional instrument transformers with optical sensors will further reduce the switchgear footprint and lower costs, while at the same time providing secondary equipment that is more flexible and secure.

Invisible substations

Not only has the technology behind substations changed dramatically in the last 100 years, but so too has their appearance. Many substations were originally built on the outskirts of cities or large towns, so appearances were not all that important. However, many of these substations have since been swallowed up by the urban expansion of the past few decades. Many who live near them find both the appearance and the acoustic pollution, caused by the humming of power transformers, unpleasant. To solve this problem, substations have been placed in buildings that are in harmony with those around it, and have therefore become "invisible." A reduced footprint – a 40 to 50 percent reduction for indoor AIS solutions and a 70 to 80 percent reduction for indoor GIS solutions – has greatly simplified this process. Locating equipment indoors increases the substation availability and reliability as the risk of primary failures, due to animals and atmospheric or industrial pollution, is significantly decreased for AIS and totally eliminated for GIS. Additionally, remote supervision of the building is possible, which helps increase the substation rounding interval. The substations are also protected against burglaries, and the irritable humming noise is greatly reduced. Underground GIS substations, making the substation truly invisible, have been implemented in city-centers around the world where substations at ground level are not permitted 4.

A reduced substation footprint means lower costs for land acquisition and preparation, the retrofitting of existing substations is easier, and the environmental impact is considerably reduced.

4 A truly invisible underground substation. The waterfall cools and hides the humming of the power transformer a, locals are invited to have their say on a proposed project b, and an underground GIS switchgear c

Two important considerations engineers must take into account when constructing new substations in urban areas are size and safety. Real estate prices mean the space required for these substations must be kept to a minimum, and higher standards for personal safety apply for substations in populated areas. To meet these specific requirements in and around cities, as well as adapting to individual requirements, ABB has developed a concept, known as the URBAN concept, for compact indoor substations up to 170 kV. Exclusively innovative systems from ABB's current product portfolio are used for indoor installations within this concept. Both air-insulated and SF_6-insulated modules

5 A MALTE prefabricated substation: old substation a, new substation b and interior of the new substation with a power transformer in the middle, high-voltage to the right, and medium-voltage and secondary equipment on the left c

can be used, depending on the actual requirements of the specific installation.

Prefabricated indoor substations

A pre-fabricated substation allows for quick and easy on-site installation, something that shortens the total project time and minimizes disturbances to neighbours. At the same time, the quality of the supply is higher due to complete factory testing before shipping. One example is MALTE, a type of distribution substation with a transformer size of up to 16 MVA. MALTE consists of pre-fabricated modules that are factory-tested before shipping. Primary and secondary cabling between the modules is prepared in a way that allows for rapid connection. On-site assembly and testing only takes one week, after which the substation is ready to be energized. Its footprint, of the order 100 m^2, is less than 30 percent of an outdoor AIS substation. MALTE 5 consists of three main modules:

- A *power transformer module* consisting of the main power transformer, a pre-fabricated foundation that also acts as an oil-pit, walls and a roof.
- A *high-voltage (HV) module* which is equipped with a removable COMPACT 52 kV circuit breaker. This module requires no foundations as it is hinged onto the side of the power transformer module.
- A *medium-voltage (MV) module* whose indoor switchgears are mounted in cubicles. In this module relay, control and auxiliary AC/DC-equipment for the entire substation is included. Like the HV module, it is also hinged onto the transformer module.

Replacing traditional instrument transformers with optical sensors further reduces the switchgear footprint while at the same time providing secondary equipment that is more flexible and secure.

As well as its small footprint and quick assembly time, MALTE, when compared to the traditional solution, offers: higher availability because the equipment is indoors; lower maintenance and rounding costs; the substation, including its foundations, can be quickly dismantled and moved; it is environmentally friendly; and finally, it is personnel and third-party safe.

Substation secondary system

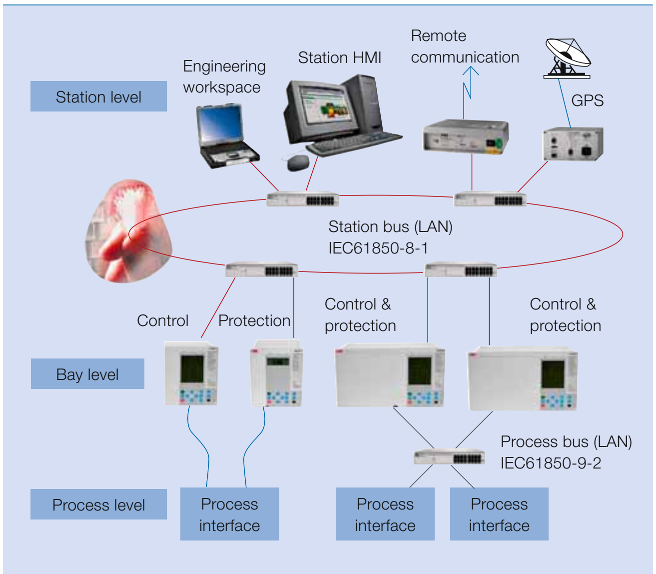
Like its primary counterpart, substation secondary systems have also changed a lot over the years. For example, the days of manual operation have been replaced by a more sophisticated form of information management. The secondary system in a modern substation 6 is used for:

- Primary system protection and supervision
- Local and remote access to the power system apparatus
- Local manual and automatic functions
- Communication links and interfaces within the secondary system
- Communication links and interfacing to network management systems

All of these functions are performed by a Substation Automation System (SAS) which contains programmable secondary devices, known as Intelligent Electronic Devices (IEDs), for control, monitoring, protection and automation. Typical characteristics of an IED include:

- It can be used for one or more switchgear bays.
- It contains independent protection functionality for each feeder.

6 The structure of a modern control and protection system



7 Pre-fabrication of a relay and control system: factory testing of complete substation equipment a, transport of whole modules to the site b and equipment in service on-site c

- It performs high-speed calculations in real-time, which will trigger a trip signal if necessary.
- The IED is intended as a combined protection and control device, but it can just as well function as a separate control or protection device.
- It can communicate with all other IEDs.

To increase SAS reliability and availability, the protection part may be duplicated to provide a redundant system. For full redundancy, all IEDs and the supporting system (like the power supply) should be duplicated, to ensure that the two systems can work independently of each other.

MALTE, a pre-fabricated distribution substation not only allows for quick and easy on-site installation, but the quality of the supply is higher.

Pre-fabrication

The pre-fabrication and pre-testing of substation automation equipment is fast becoming the norm for a modern substation. The system is delivered in sections containing all the required functions for a part of the primary system, and these sections are then simply connected together via an optical-fiber 7. Pre-fabrication has many advantages such as:

- The total costs can be kept lower due to optimized manufacturing and testing.
- The quality is higher because the module has been fully tested in-house and is shipped with all the wiring intact.
- Because much of the assembly and testing is completed before shipping, the time spent on-site is considerably reduced.
- Pre-fabrication is suitable for both “green field” and retrofit projects.
- Future retrofit is simplified and can be done with shorter outage time by replacing the complete pre-fabricated building.

Communication

Effective and fast communication between IEDs is essential in an SAS. Numerical communication had been used for many years in substations delivered by ABB, but a lack of standardized protocols limited the efficiency of SAS and restricted the mixing of ABB and non ABB IEDs. To overcome this problem, ABB has actively participated and supported IEC in the development of a standard for substation communication, known as the IEC 61850 communication standard [1].

Modern substations are generally remotely operated, and communication between the substation and the remote control center is via a wide area network (WAN). Nowadays, new overhead lines or power cable connections are equipped with optical-fiber to enable protective system communication and for the WAN.

A look into the future

The last 100 years have seen the economy move from the industrial age to the information age. A host of fascinating ideas, in particular the World Wide Web, have changed how many people and companies live and work. For example, the availability of the internet to companies like ABB means that customer contact is greatly simplified and faster. Projects can be executed using a common database assessed by both parties.

Future substation power handling equipment will be even more integrated and compact, while measuring functions and all of the secondary functions will be done using fiber-optics.

In the future, substation power handling equipment will be even more integrated and compact, while measuring functions and all of the secondary functions will be done using fiber-optics. In other words, tons of porcelain, copper and iron will be superseded by just a few fiber-optic connections. This will further speed up the delivery process, reduce the substation footprint, and make it more environmentally friendly.

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Reference
[1] **Frei, C., Kirrmann, H., Kostic, T., Maeda, T., Obrist, M.** Speed and quality. *ABB Review* 4/2007, 38–41.

At the pulse of power

ABB is never short of solutions for operating and controlling the grid

Claus Vetter, Neela Mayur, Marina Öhrn

As the global demand for power is growing, so too are the electrical grids. In growing economies, like those of China and India, the need for power is straining the existing system's capabilities, while in other parts of the world, ongoing regulatory efforts force a continuous restructuring of the vital infrastructure. Maintaining what can only be described as a very dynamic infrastructure involves many complex operations. However, irrespective of the complexity of this task, the reliable supply of energy must always be the prime goal of any provider of electrical energy system solutions.

As the world's number one provider in the field, ABB has been helping customers manage their grid and play a vital role in the operation of power systems for many generations. Continuous improvement and innovation have led to the development of modern and comprehensive solutions for controlling and operating the grid. ABB's Network Manager Platform, for example, provides the capabilities for traditional supervisory control and data acquisition (SCADA), solutions for generation and transmission management, distribution and outage management capabilities, as well as Business Management Systems for energy trading. However impressive these solutions may be, a company must never relax. An ever-changing market climate means that ABB is constantly adding to or upgrading their already extensive portfolio of energy operation solutions.

Transformers and substations

Every plug and outlet in a household, industry or in any consumer's facility connects to a myriad of lines and connections, which form a network similar to the veins of the cardio-vascular system. Distribution networks are constantly changing shape and size whenever consumers are added, appliances are connected and disconnected, or parts of the system undergo repair or maintenance. Built as star or ring structures, meshed or unmeshed, as cables or overhead lines, the distribution network finally connects to substations. Here, at the border of the transmission or subtransmission system, the bulk of the power is fed into the distribution grid, converted, regulated and controlled. The transmission grid acts as the arterial lifeline in that it delivers energy to all parts of the system, and any disturbances will have a widespread impact. For example, millions of lights go out, public infrastructure may collapse, and the economy and people suffer. Therefore, the reliable supply of energy must always be the main goal of any company providing solutions for the electric energy systems around the world.

Transmission and distribution solutions

For many decades, ABB has been at the forefront of systems development – in particular, information technology (IT) systems development – for power transmission and distribution. Since the development of the first remote control system for power plants in the 1920s by ASEA and BBC, the company has come a long way with its IT systems of today that not only help customers manage their grid, but which also allow them to play a vital role in the operation of power systems. ABB solutions range from a pure SCADA system, to advanced transmission and distribution systems which ensure secure and stable operation and prevent blackouts. Furthermore, modern Energy Information Systems exist to help the operator ensure that the grid is operated in an economically optimized way. All the required business information is available at the click of a mouse.

> ABB's Network Manager offers a complete range of functions to fulfill the needs of transmission network operators and of combined network and power generation operators.

ABB's Network Manager offers a complete range of functions to fulfill the needs of transmission network operators and of combined network and power generation operators. These range from the analysis and optimization of day-to-day operations and short term scheduling to the real-time dispatch and control of generation.

ABB's Network Manager platform provides an open system architecture and versatile integration of ABB enterprise applications or third-party software. It provides the capabilities for traditional SCADA, solutions for generation and transmission management, distribution and outage management capabilities, as well as Business Management Systems (BMS) for Energy Trading.

BMS are market operations systems that provide complete software solutions for managing central energy markets for Independent System Operators (ISOs), power pools and Regional Transmission Organizations (RTOs). A typical BMS provides tools for day-ahead or real time generation scheduling, and is delivered on an open architecture platform that features state-of-the-art interfaces to other software systems. BMS also delivers an e-commerce platform to administer all aspects of a competitive energy market, and it provides settlements and metering interface.

The company's Generation Management System (GMS) allows for advanced operation and optimal scheduling and analysis of generating

Scope of supply for Network Management offerings

power plants. This includes load forecasting, in-flow forecasting, transaction evaluation, bidding, unit commitment, hydro-generation scheduling and optimal usage of generation resources with integrated scheduling and trading, multi area load-frequency and tie line balancing.

ABB's Energy Management Systems (EMS) extends SCADA functionality (to form the SCADA/EMS solution) with applications such as state-estimation, which provides a detailed and accurate picture of the network with a time resolution of seconds to minutes. Contingency analysis, also a part of EMS, helps operators to run "what-if" scenarios for different network conditions to determine, for example, what corrective actions are needed to enable overloads to be mitigated in an optimal way, or to assess reactive power balance and margins, or even to manage loading limits. In short, EMS allows utilities to support secure and efficient operations in regulated and deregulated markets by:

- Managing active power flows and voltage profiles
- Rapidly determining operational security
- Detecting and mitigating congestions
- Identifying voltage collapses
- Performing analysis on recorded disturbances and simulating restoration tasks
- Providing a training simulator

However, EMS applications are not ideally suited to modeling the details of the distribution level network. In fact, the network model size, in terms of power systems objects, is usually a factor larger in distribution systems than in transmission systems. To compensate for this, Distributed Management System (DMS) applications increase SCADA functionality capabilities (to form the SCADA/DMS solution) in fields where EMS applications fall short. DMS can handle feeder reconfiguration, reactive power component scheduling, and line cut modeling. It also supports constantly changing network topologies (due to extensions, maintenance or temporal local outages), and allows for a geographical view of the distribution network 1. An outage management function provides the capability of integrating customer information and trouble call management systems into the existing SCADA/DMS system, thus allowing operators to mange the distribution network with a fully integrated system.

Business Management Systems (BMS) are market operations, systems that provide complete software solutions for managing central energy markets.

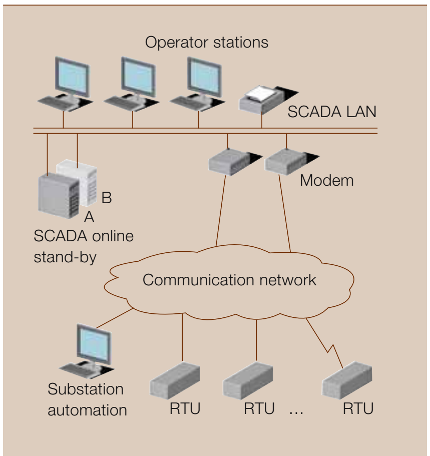
Finally, ABB's utility communications solutions complete the portfolio, providing functionality for operational and corporate communication networks. Broadband and power-line carrier solutions enable the transmission of voice, and vital control and protection signals for the operational needs of electric utilities.

Making the case

Market rules affecting business operation are constantly changing. Currently three factors have been identified which influence how power grids are operated, and the first of these focuses on the continuously increasing demand for power. Growing worldwide economies need more power, forcing utilities to operate their systems closer to their physical limits. This in turn reduces supply-margin security and puts more stress on the network equipment[1].

At the same time, with growing networks and interconnections between countries[2], the influence of economics on the supply of power, the second factor to be identified, is greater than it has ever been. In other words, in-

1 A geographically distributed process



Footnotes

1) Network expansion happens at a slower rate due to environmental and economic considerations.

2) The European UCTE network, extending from northern Denmark to southern Greece, and from the west of Portugal to eastern Romania and Bulgaria, currently supplies about 450 million consumers with an annual consumption of approximately 2,300 TWh.

stead of physics and safety influencing the behavior and plans of electric utilities, as they did in the past, market laws are now the driving force behind the flow of power in the grid. This change demands connectivity to many non-operational IT systems, such as ERP (Enterprise Resource Planning) and CRM (Customer Relationship Management) which carry business relevant data.

The third and final factor focuses on the environmental side-effects of increased power generation, especially the level of CO_2 emissions. The spotlight is now firmly on both the efficient use of energy, and the increased usage of renewable, distributed energy.

Companies like ABB can easily cope with these factors. The solutions described above go a long way in addressing the changing nature of the market. However, some technology initiatives were needed to further master these challenges, and these are described in the following paragraphs

Regulatory influence, economics and the growing use of standard IT infrastructure are fostering the integration of IT systems beyond their original boundaries.

Innovative solutions

While traditional substation automation solutions safeguard humans and equipment from operational failures in milliseconds, SCADA/EMS systems work on the minute time-scale when dealing with network operational conditions. However, with many global power grids already operating closer to their limits, the time to act and react to disturbances in the network has become shorter and more valuable. Traditionally, many power system applications report overloads or voltage sags on individual lines or nodes in the network. However in order to deal at speed with the system-wide consequences of such problems, a more complete picture is required. This picture can be supplied using ABB's Phasor Measurement Unit (PMU) based solutions. These provide a system-wide view of the network, thus enabling the operator to take corrective actions quickly in case of a critical system state. Highly accurate results are provided when PMU measurements are integrated into ABB's state estimator solution. These same PMU measurements are also used to assess the general power system condition as part of ABB's Wide-Area-Monitoring and Control portfolio. Operators can then take corrective actions (eg, use FACT devices to control the power flow) based on information concerning the entire network.

In a typical emergency situation, operators are usually overwhelmed with massive amounts of data and alarms. ABB is currently investigating different solutions to support utilities in this regard.

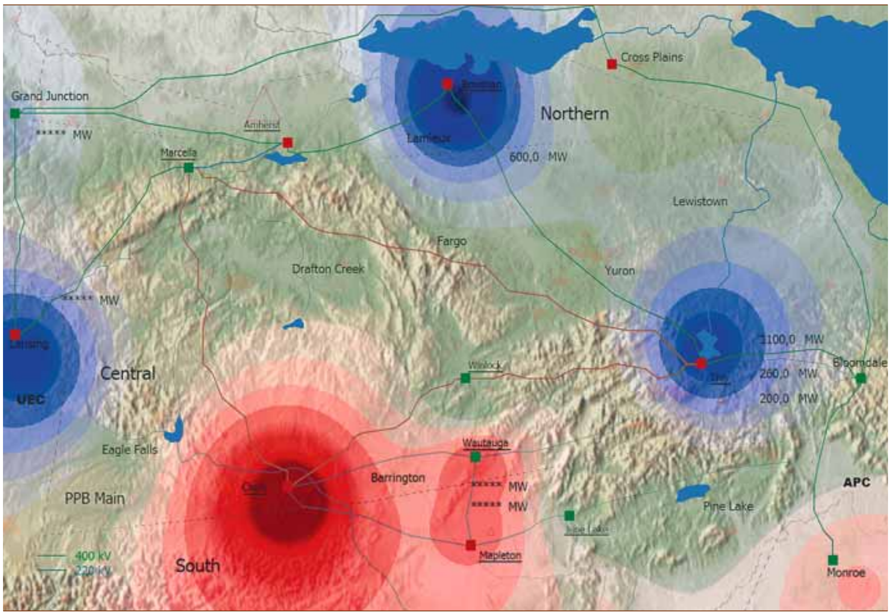
First of all, the operational awareness of the users in the control room is sharpened if more visual information about the power system state is provided. Usually power system collapses are a result of cascading failures in the grid, so it is important not only to view individual components, but also system-wide developments must be easily identified. The inclusion of voltage or frequency distribution contour maps 2, or of grid-wide power oscillations are examples of the extra information that could be supplied when observing the state of a system state before a critical event occurs.

With the meshing of large systems, not to mention the growing network sizes, the number of errors and alarms an operator has to deal with can be overwhelming. ABB supports its customers with an alarm management system capable of identifying root causes. This system helps to filter alarms and suppresses redundant events so the operator can react quickly on system failures at the right time.

ABB's alarm management system helps to filter alarms and suppresses redundant events so the operator can react quickly to system failures at the right point in time.

Regulatory influence, economics and the growing use of standard IT infrastructure are fostering the integration of IT systems beyond their original boundaries. However, the technical challenges of integration are significant. Cyber-security related issues further complicate the situation. With NERC/CIP cyber-security regulations[3)]

2 Dynamic Network coloring in Network Manager – Red/blue colors indicate a deviation from nominal voltage levels (high/low)



now in effect since the beginning of 2008, ABB Network Management is constantly developing or using a full set of tools to provide end-customers with the possibility to comply to these regulations within the scope of supply. With its SCADA/EMS solutions, the company ensures early in the development that: involved personnel are well trained on cyber-security standards; code access is logged and monitored; the software follows best practices in threat modeling; and the accompanying coding practices are followed. Compliance is also required during system deployment on activities such as restricting the number and types of services needed to fulfill operational requirements to the absolute minimum, and hardening the system by removing or disabling all unnecessary network connections, services and file shares, while ensuring that all remaining functions have appropriate security settings. However, it is important to understand that security is about risk management and that optimal security can only be achieved by maintaining close co-operation and contact with customers. ABB is also using internal (for example, ethical hackers) and independent facilities (eg, US Idaho National Labs) to test the vulnerability of its Network Management system. In short, ABB is developing its systems together with its customers with the aim of achieving two very challenging goals:

- Opening up the systems to met the ever demanding economic objectives, while at the same time
- Safeguarding the systems from unwanted intrusion or tampering

Energy efficiency and the increased use of renewable energy resources are very important factors in the development of transmission and distribution management solutions. On the high-voltage level, the integration of wind generation technologies is a major topic as confidence in wind power continues to grow. ABB's Network Management system helps to schedule and balance wind power's stochastic influence in an economically optimal way without jeopardizing system stability. On the distribution level, the influence of distributed generation (solar, biomass, combined-heat-power, etc.) is changing power flows in the network. In former times, power flow was uniquely directed from the generation level to the distribution level via the transmission level. Nowadays, the growing in-feed of renewable energy at the low-voltage level needs to be dealt with. At the same time, the installation of more "intelligent" devices in the field produces a vast amount of varying data. The analysis of this data helps to determine the most optimal ecological and economical solution for dispatching distributed generation. In the future, ABB's solution will help to determine the potential for adding distributed energy resources. The utilities can then concentrate on finding suitable network extension solutions.

ABB is adding capabilities for emissions trading to the "market infrastructure support" software that forms part of its BMS. BMS' "Market Operations" applications are designed to manage bids and offers (including energy, reserves, congestion, etc.) from market participants, and emissions trading (CO_2, NO_x, etc.) is a natural extension to the capabilities of these systems, given that the practice of trading emissions is now common in Europe under EU directives and NO_x is actively traded in the US.

A typical control room

Energy efficiency and the increased use of renewable energy resources are very important factors in the development of transmission and distribution management solutions.

Final thought

With societies so increasingly dependent on the reliable delivery of energy, a secure, affordable and ecologically sustainable supply is top of the agenda for all utility companies. Behind the plug, ABB is well prepared to take on these challenges with a full range of transmission and distribution solutions.

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Footnote

[3] See http://www.nerc.com/~filez/cip.html (NERC /CIP webpage) (December 2007).

When grids get smart

Intelligent automation for distribution networks

Cherry Yuen, Duncan Botting, Andrew D.B. Paice, John Finney, Otto Preiss

The traditional delivery of electricity from large, centrally generated electricity units via reliable transmission grids onto tapered distribution networks must now be complemented by distributed generation to satisfy changing needs of modern society. The request for renewable sources to generate electricity, combined with the demand for greater energy efficiency, is redefining the traditional delivery mechanism.

On average, the majority of today's electricity generation and distribution systems waste over 60 percent of their energy in the form of heat before delivering any useful energy to the end user. One promising means of reducing these losses is through the distributed generation of electricity closer to the end user. This has led to a huge increase in demand for solutions such as micro-generation in homes and in industry to be linked with heating and cooling (micro combined heat and power [micro CHP] units) thus increasing total useful energy efficiency levels up to 85 percent.

Locally generated renewable sources such as wind, solar and micro CHP are creating new and challenging issues. While in the past the energy flow was unidirectional from the central source to the distributed consumer, now the two-way power flow of distributed generation must be managed. This power requires real-time coordination with the traditional power generation units in the grid. Distribution Network Operators (DNOs) now face the challenge of providing networks and services that can deal with this new paradigm – issues that were traditionally managed at the transmission level.

From passive to active grids

Distribution networks are thus moving from traditionally passive networks (ie, those that were planned for particular peak loads and for use as fit-and-forget networks) to more active or dynamically adapting networks in order to manage the increasing demands placed on them. Many small generator units could be run as one large power source, called a virtual power plant (VPP). The connection of smart "white goods" in the home (eg, refrigerators or freezers) could be managed by the DNO to provide active and reactive load control in the local network, taking smart metering to a new level of sophistication.

Energy storage solutions that smooth the capacity constraint issues could be part of what is now seen as an intelligent- or smart-grid future, which is based on active network management (ANM) and the associated intelligent automation system. Such an intelligent automation system also is required to assist the developing commercial and regulatory structures that are projected onto the physical electrical grid. The liberalized markets now have fragmented commercial stakeholders that require different, more flexible administrative solutions than the traditional vertically integrated control and command structures. Regulators require different parts of the supply chain to act and record transactions in a robust manner, while at the same time provide evidence of the most cost-effective delivery of their services.

An optimal smart electricity grid would – by utilization of the latest information technologies – be able to largely control itself. That is, it would be able to accept any kind of generation source, deliver power of any quality on demand, diagnose itself, and even heal itself through intelligent use of redundancies.

Governments are taking action to accelerate research, development and deployment projects to realize this vision of active network management. Examples include the IntelliGrid Initiative led by the Electric Power Research Institute [1] and the SmartGrids European Technology Platform [2] sponsored by the European Commission 1. ABB has been instrumental in the leadership of this new and exciting technology-intensive area and has been deeply involved in developing Europe's smart-grid vision.

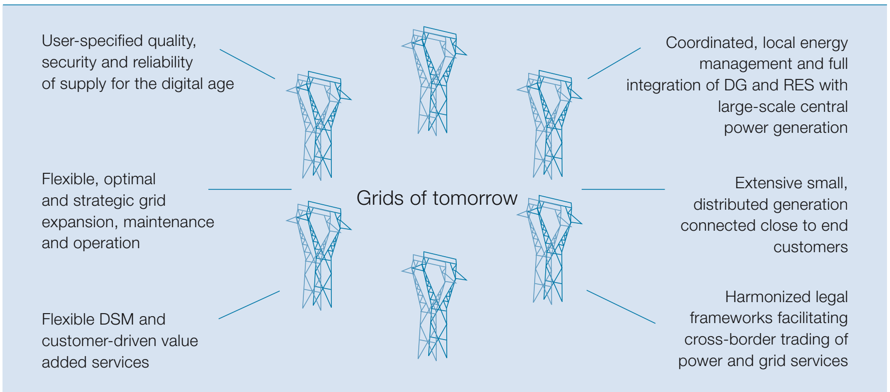
Technical challenges

Introducing this new smart-grid concept opens the door to previously unknown challenges. For example, the power flow may reverse as the generation capacity of one area exceeds the local demand and is used to compensate the load requirements in a neighboring area. These effects may be restricted to the low-voltage level, but may also be felt at the medium-voltage level, as illustrated in 2. Network congestion may result when the transfer capacity of the lines is reached or exceeded. This problem is exaggerated when the distributed energy sources are not close to the main energy consumers. The automation system that manages those challenging situations must have access to the real-time dynamic changing of the whole grid. This requires additional measurement, state estimation algorithms, and flexible control and protection settings.

Furthermore, the automation system should be intelligent enough to cope with generation profiles that may change with the weather and the time of day (eg, wind or photovoltaic generation). The result will be a continually changing distribution of power flow and direction, in contrast to the relatively stable, unidirectional power flow typical of a distribution network today. All of these functions require greater use of fast and reliable Information and Communication Technologies (ICTs).

The amount of data required to perform the various smart-grid functions

1 Vision of future grids (from an EU report on European SmartGrids Technology Platform). DG: distributed generation; RES: renewable energy resources; DSM: demand side management



is enormous and diverse. Data come from different sources and systems (eg, SCADA[1]) and energy market platform, and are both historical and real time with sampling rates varying according to the specific functional and communication requirements. In the new ITC system, a balance between additional sensors and sophisticated state estimates must be found to keep costs low.

The next challenge is to integrate the new ICT architecture with the infrastructure that is already installed by the utilities. Many DNOs are operating electrical and ICT infrastructure that is at least 10 years old and not fit for the rich data flow necessary for ANM. The use of different data communication standards and the inadequate bandwidth of the communication channels are a barrier for an implementation of smart grids in the near future.

Besides the management of the technical performance of a smart grid, the ANM also should support the manifold administrative tasks of the grid operators. In a smart grid, generation unit operators and distribution infrastructure providers are different legal entities with the same need for automating the accounting procedures of their business.

The way forward

Building the next generation of active power delivery networks requires a mixture of new technology, existing technology deployed in new ways, existing asset infrastructure utilized in an optimum way, and changes in operating practices by electric utilities. Progress in such a complex, multi-stakeholder research and development effort can only be made with collaborating teams. ABB is involved in the following team-based projects.

AuRA-NMS

Autonomous Regional Active Network Management Systems (AuRA-NMS) is a collaborative research and development project sponsored by the UK Engineering and Physical Sciences Research Council (EPSRC), that seeks to demonstrate new network operation concepts in the United Kingdom. In addition to ABB, the consortium includes two network operators (ScottishPower and EDF Energy) and the contributions of seven UK universities, including Imperial College London.

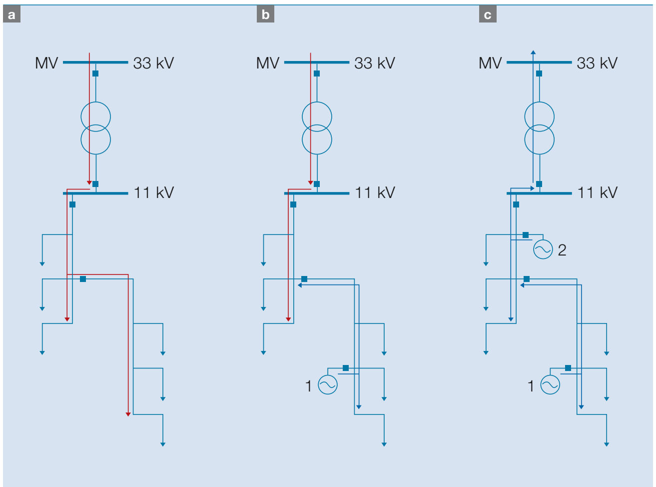
An optimal smart electricity grid would be able to largely control itself.

The goal of AuRA-NMS is to demonstrate the benefits of active network management using a distributed architecture that is integrated into existing control and asset infrastructure. This includes the use of innovative battery storage to understand the merits of trading opportunities, the support of constrained capacity related to overhead lines and cables, and stability control of the network due to various types of distributed generation. The project also aims to provide automated solutions to complicated constraint management.

ABB's new Station Automation Series COM 600 is the network management system controller used in the project. Designed to complement the substation automation and network management systems already in service by ScottishPower and EDF Energy, the COM 600 series offers interoperability and extensibility through support of the IEC 61850 standard, and provides a certain level of legacy protocol support for the DNOs' existing feeder automation devices.

Furthermore, ABB is deploying a new energy storage system at an EDF Energy substation where wind generation interfaces with a weak medium-voltage network. The new dynamic power compensator, SVC Light Energy Storage, is a revolutionary combination of ABB's SVC Light STATCOM[2] with a record-setting 6-kV DC battery system composed of efficient and environmentally friendly energy storage cells.

2 Uni-directional flow a, reverse flow only in one section of the 11-kV feeder b and reverse flow via a 33-kV/11-kV transformer c



Microgrids

This project, supported by the European Union, seeks to identify the promise and address the challenges of proliferation of microgrids in Europe. A microgrid is a loosely defined, self-sufficient interconnection of distributed generation, residential and industrial load in a low-voltage network without a persistent connection to a larger, stronger grid. In addition, the creation of ad hoc microgrids by islanding pockets of a larger network has the potential to stop cascading outages while keeping critical loads online.

ADDRESS

Active Distribution networks with full integration of Demand and distributed energy RESourceS (ADDRESS) is another ambitious project involving several utilities, multiple power-system and white-goods vendors, telecommunications companies and numerous universities. Their goal is to develop a commercial and technical framework to realize the full benefits of active networks with distributed resources.

Active network management

Current network management practice is mostly based on a centralized SCADA system, which regularly gathers online measurements from the

Footnotes

[1] SCADA: Supervisory Control and Data Acquisition

[2] STATCOM: static compensator

telemetric points in the distribution network. The traditional communication infrastructure of SCADA systems has been designed to acquire data about once or twice every minute and to send out control commands whenever necessary. A higher data acquisition rate has not been required by the existing applications. However, these low data rates are insufficient when more complex distributed generation networks must be managed.

To overcome this problem, one can either improve the communication infrastructure to enable faster data rates, or store the online measurement data in a local substation and exchange the relevant data among the substations to perform sophisticated real-time applications. The amount of data stored is less than that stored for the SCADA database, because each substation is responsible only for its own part of the network. It can then allow data to be stored at a higher frequency, eg, once per second or microsecond, depending on the application. Since most data is stored locally, the requirements for communication from substations to network control centers are relaxed.

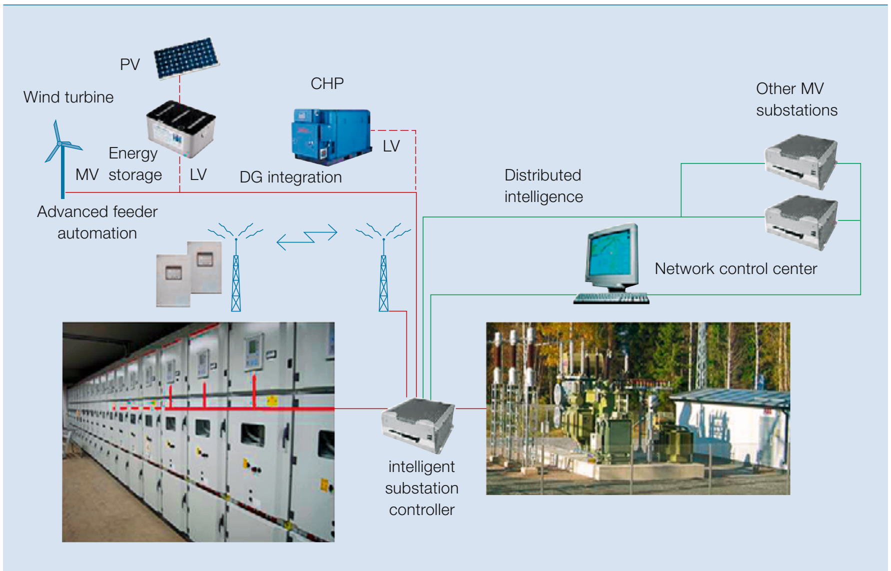
This promising approach requires decentralized algorithms that seamlessly integrate into a now reduced central SCADA control function to ensure optimal local operation. The localized controllers have sufficient intelligence that enables them to coordinate with each other, and thus ensure reliable global operation.

Indeed, some of these new required functionalities are similar to those available in the energy management system (EMS) today – eg, meshed load-flow analysis and generation forecast – which now have to be used at a local level. More importantly, instead of passively responding to events in the distribution network, an active network should be able to predict (based on monitored and trended information) what is likely to happen and act on the data in a proactive manner. This forecast applies to both generation and load.

A further important feature of an active network is the ability to adjust the settings of the Intelligent Electronic Devices (IEDs) – eg, protection relays – according to the real-time operating states of the network. While traditional relays support very few settings to adjust themselves to the power flow conditions, the integration of distributed generation requires an increased number of settings to operate the network efficiently and reliably in real time. This results in a more sophisticated, dynamic setting based on online data and careful coordination of all concerned relays.

3 shows an example of active network management based on decentralized control. The intelligent substation controller, which is installed in several medium-voltage substations, has gateway functionalities, ie, it can translate data in the process communication protocol to the network control center communication protocol and vice versa. In addition, distributed intelligence is hosted in these controllers.

3 An active management system based on decentralized control



First steps taken

The highly integrated, multifaceted approach to realizing an intelligent or smart grid can only be managed with the collaboration of all involved stakeholders. A small but significant part of this cooperation addresses the intelligent automation systems for distribution networks and in addition the implementation of active network management. ABB is making important contributions in all aspects of this work, providing new devices that will enhance the local power supply as well as researching the communication and control technologies that form the basis of an intelligent distributed system.

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[2] www.smartgrids.eu (November 2007)

Transport or transmit?

Should we transport primary energy resources or transmit them as electricity?

Alexandre Oudalov, Muhamad Reza

When we think of the methods by which primary fuel as found in mines and deposits is converted to the electricity that makes our lights work, we often consider the various steps of the extraction and conversion process. The optimization of this process, however, is incomplete if it does not take a further aspect into consideration: transportation.

Should the power stations be built close to the load centers, with the fuel being brought there mechanically (for example, by rail, ship or pipeline), or does it make more sense to generate the electricity close to the primary energy deposits, and use electrical wires for bulk transmission?

Projections by the International Energy Agency indicate that the global demand for electrical energy will double between today and 2030. Coal and natural gas will be the world's fastest growing sources of electrical energy, accounting for around 70 percent of the increase in electric energy generation over the next 30 years 1. Since sources of primary energy resources are usually distant from the main load and population centers, their exploitation usually requires the bulk transmission of electrical energy (>500 MW) or the equivalent transportation of primary energy resources over a long distance (>100 km). Factbox 1 illustrates a variety of energy transport scenarios. These display different levels of efficiency, reliability and environmental safety. These scenarios are characterized on the one hand by the type of primary energy resource used, and on the other hand by the transport system deployed.

The methods adopted for moving primary energy resources to power plants and then moving the electric energy to load centers is determined by a complex decision making process and depends (amongst others) on the amount of energy to be moved, the distance over which it must be moved, capital and operating costs of the transport system and amount of existing infrastructure [1–3]. Additional factors affecting such a decision are linked to externality cost, which is related to the environmental and social consequences of energy transportation. The authors analyzed the position of ABB's "wire" technologies (HVDC and HVAC) when compared to various methods of transporting primary energy and generating electricity closer to the load centers.

Bulk energy transport model

A bulk energy transport (BET) model was constructed to address all relevant combinations of problem scenarios and technologies, embracing common practice techniques for life-cycle cost analysis with monetization of externalities and supporting sensitivity analysis. 2 illustrates main components of the BET model for a comparison of alternative energy transport options (further details can be found in [4]). The bulk energy transport analysis considers two major options: the transmission of electric energy and the transport of primary energy resources. A total cost of each transport option consists of capital, operating and externality costs Factbox 2. Together with the cost of electricity at the point of delivery to the load centre, these indices are used to rank alternative energy transport options.

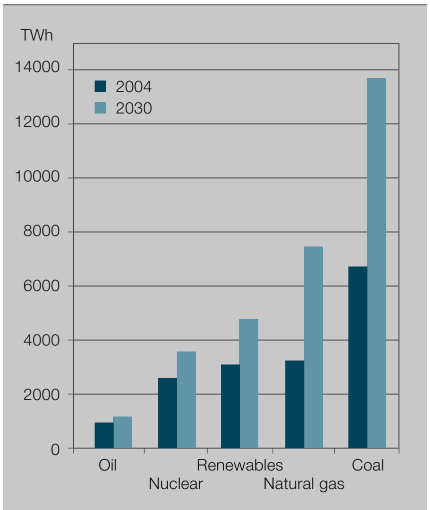
HVDC technologies provide strategic opportunities to reduce externality cost.

Air-pollution implication

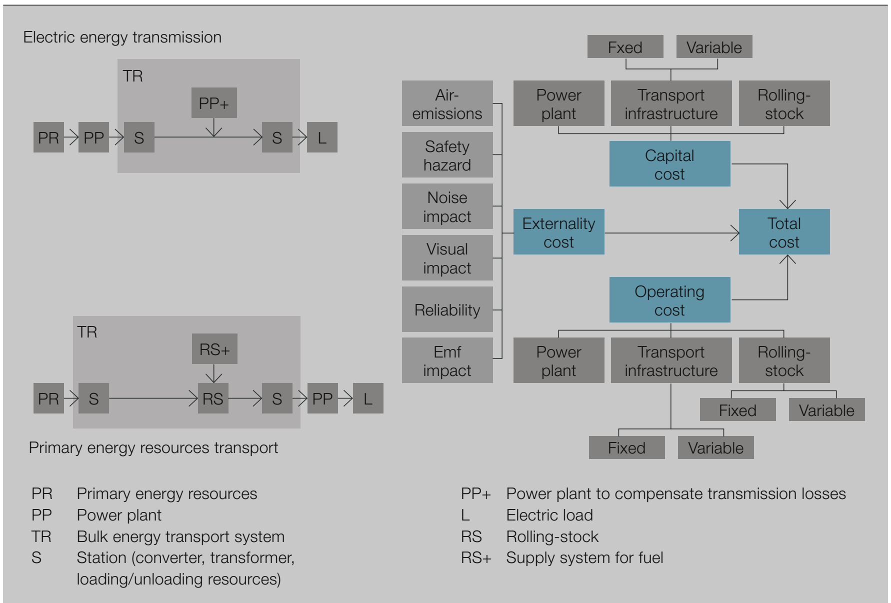
Using an example of air-pollution emissions, the following section illustrates an estimation of externality cost. Air-pollution caused by generation and energy transport includes pollutants emitted by combustion of primary energy resources at the power plant, by rolling-stock engines and pollutants released by the combustion of the additional primary energy resources required to cover transmission losses. The study considered the following air pollutants: CO_2 for global climate change, NO_x, SO_2 for acid rains and aerosols and suspended particulate matters (PM). It also accounts for different air emission-capturing capabilities of power plants and rolling-stock. The total air emission externality cost is a single indicator which aggregates air emission costs of all pollutants for the option being looked into.

For example, the annual externality cost of CO_2 emission in the case of electricity transmission paired with mine-mouth coal-fired generation is calculated from the following parameters:
- Emission factor in tons of CO_2 per ton of combusted coal

1 World Electricity Generation by Fuel, 2004-2030, Source: IEA, 2006



2 Bulk energy transport model



Factbox 1 Alternative bulk energy transport scenarios

Primary energy resource	Moving fuel by						
	Wire	Rail	Barge	Vessel	Pipeline	Truck	Conveyor
Coal	HVAC HVDC	Unit trains	Tows	Vessel	Slurry, coal logs, synthetic gas	Impractical for >100 km	Impractical for >50 km
Natural gas		Impractical		LNG vessel	Overland, underground	Impractical	Physically impossible

Transformers and substations

Factbox 2 BET Model components: capital, operating and externality costs

Type	Power plant	Transport infrastructure		Rolling stock	
		Fixed	Variable	Fixed	Variable
Capital cost is linked to production, construction and decommissioning of infrastructure	Power plant capacity. Differs for each energy transport scenario due to the power plant characteristics and the additional power required to compensate transmission losses.	Primary energy resources loading/ unloading facilities or converter and transformer stations at both ends of the route	Transport route: rail track, pipeline, high-voltage overhead line or cable	Circulating rolling-stock: unit trains, tows, vessels	
Operating cost is linked to primary energy resources production and transportation, power generation and transmission, compensation of losses	Fuel and maintenance cost	Electric losses in converter and transformer stations or the lost primary energy resources during loading and unloading of rolling-stock plus maintenance cost	Electric losses in conductors or the lost primary energy recourses during transportation plus maintenance cost	Maintenance cost	Fuel cost
Externality cost is related to the environmental and social consequences of bulk energy transport. If environmental regulations removed all externalities, these costs would be zero. However, it is not efficient for environmental regulation to remove all externalities. Rather, a standard should be set at the level where marginal social benefit of abatement equals marginal social cost. At this level, there will still be externalities that should be considered in decisions about transport. Even assuming that environmental regulations are properly set, the remaining externalities might influence choosing one option for BET over another, eg, an underground cable for transmission rather than overhead lines. In the BET Model, air pollution emissions, safety hazard, audible noise, visual (aesthetic) effect, and EMF impact are considered as major “building blocks” of the externality cost.					

- CO_2 emission reduction efficiency of coal-fired power plant (influences capital and operating costs)
- Consumption rate of coal in tons per year
- Estimated future emission tax per ton of CO_2

In general, air-emission taxes reflect the health and ecosystem impacts of the pollutants being taxed. Today they reach the level of 25–40 $ per ton of CO_2 in some countries [5]. Taking into account the fact that CO_2 emissions have a global effect on the environment, the emission tax does not depend on the geographic location of power plant and energy transport infrastructure within a specified environmental regulation area. However, the other pollutants considered do have a strong local environmental impact. Therefore, power plants and infrastructure for energy transport located close to load centers are subject to much higher emission taxes than those in remote locations.

Case study

The results of a comparative analysis of a set of bulk energy transport scenarios defined according to state of the art technologies and typical use on the mainland are presented in the following case study. The scenarios considered deal with the transportation of energy from a coal mine (low sulfur, sub-bituminous coal) to the load center by the following means 3:

- Coal by wire (HVAC and HVDC overhead lines and HVDC cable) coupled with a mine-mouth coal-fired power plant
- Coal by rail coupled with a coal-fired power plant in the vicinity of the load center
- Coal to synthetic natural gas (methanation) by pipeline coupled with a gas fired power plant in the vicinity of the load center.

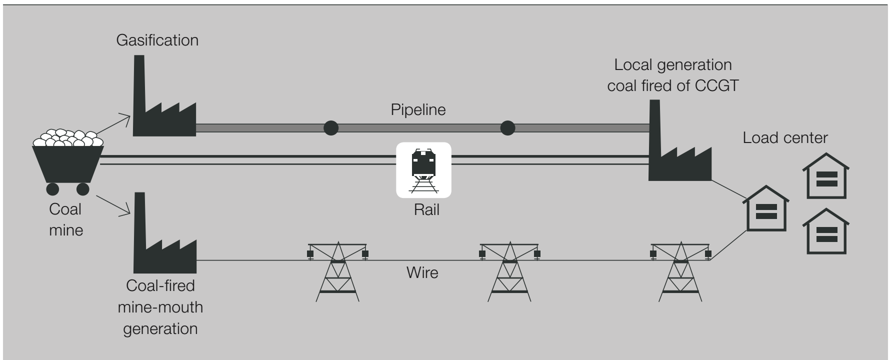
This study is based on the scenario of transporting 1000 MW of electricity (or the shipping of the primary energy resources needed to produce 1000 MW) over a distance of 1000 km. In this first phase of the analysis, it is assumed that:

- Externality cost is not implied in the “business as usual” (BAU) case
- All required data on capital and operating costs are available
- Rail track, power transmission lines and pipeline do not exist and must be built.

4 illustrates the cost of electricity at the load center including generation and energy transport. The comparison of different bulk energy transport scenarios in the BAU case leads to the following principal conclusions:

- The ranking of these bulk energy transport systems mainly depends on the capital cost
- Overhead HVDC lines offer the lowest electricity cost,
- The operating cost is the largest component of the coal by rail option

3 Bulk energy transport scenarios



- Underground HVDC cable is the most costly of the five options.

The BAU case showed that overhead HVDC transmission option is clearly more advantageous than transporting primary energy resources to the load center and generating electricity locally.

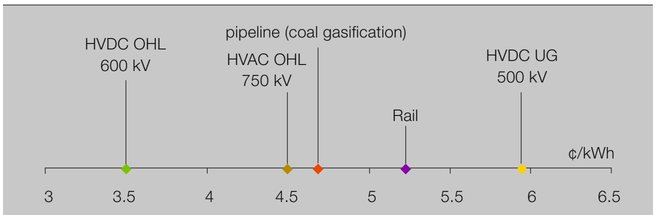
In the next phase of the study, the implication of externality cost (and in particular CO_2 emissions) on the ranking of the different bulk energy transport options were considered. 5 shows the variation of cost of electricity at the load center due to a variation of the CO_2 emission tax in a scenario that sees no CO_2 capture. The left end of the graph shows the zero tax scenario (identical to the BAU discussed above). From here, the electricity cost increases with CO_2 emission tax for all options. Underground HVDC cable has the highest cost because of the higher amount of coal that must be fired to compensate electric transmission losses. An overhead HVDC transmission line is a cheaper option, entailing a CO_2 emission tax of less than \$100 per ton of CO_2, but it can be surpassed by a coal to gas with pipeline option when the “break-even CO_2 emission tax” of \$ 100 per ton of CO_2 is reached. The coal by rail option becomes more economic than overhead HVAC transmission lines for a tax rate of \$150 per ton of CO_2. Present CO_2 emission taxes in Europe are in the range of \$ 25–40 per ton of CO_2.

A very high CO_2 emission tax makes CO_2 sequestration economically attractive. Capturing and nearby storage of 80 percent of CO_2 emissions (this is an economically justifiable limit), the overhead HVDC transmission line would be surpassed by the coal to gas by pipeline option only if the “break-even CO_2 emission tax” climbs to \$ 300 per ton of CO_2 6. Furthermore, the overhead HVAC transmission line will become more expensive than the coal by rail option at a CO_2 emission tax level of \$ 1300 per ton of CO_2. Thus, the capture of CO_2 increases a competitiveness of “wire” technologies (the costs of CO_2 capture and sequestration are taken into account).

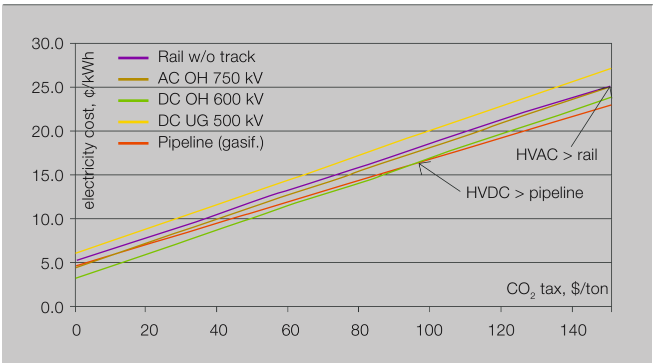
According to the BET model, an externality implication on bulk energy transport shows that early conversion of coal to electricity and transmission with HVDC technologies demonstrates a significant improvement over the conventional overland transport of primary energy resources. HVDC technologies provide strategic opportunities to reduce externality cost. The authors believe that it is highly probable that long distance bulk energy transportation will shift from moving primary energy resources to electric energy transmission.

In regard to these predictions it should be noted that the input data used is afflicted with a certain degree of uncertainty.

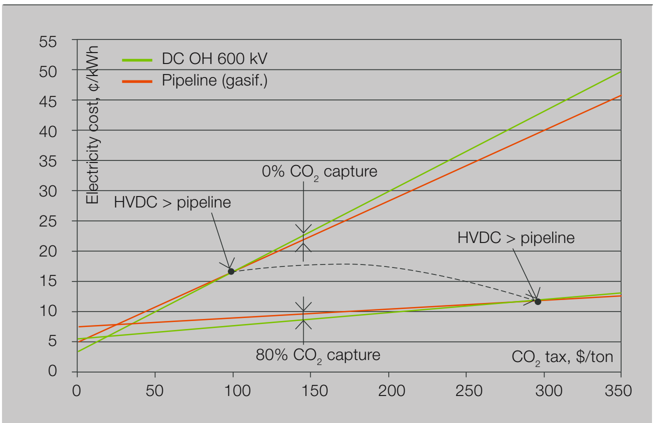
4 Cost of electricity at the load center (BAU case)



5 The impact of CO_2 emission tax on the cost of electricity at the load center



6 The “break-even CO_2 emission tax” for overhead HVDC line and coal to gas by pipeline for 0 and 80 percent of CO_2 capture



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Powering platforms

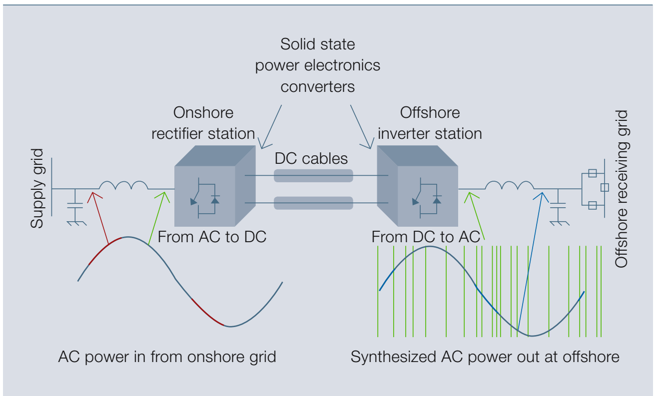
Connecting oil and gas platforms to mainland power grids

Rahul Chokhawala

Provision of electrical power and other forms of consumable energy start with the exploration of primary energy. These primary sources are often located in remote places and their operation poses significant challenges for exploration companies. Oil and gas platforms far offshore are a prominent example of these sites, at which safety, environmental constraints and life-cycle economy are high on the agenda. With HVDC Light®, ABB offers the most economic solution with the smallest environmental footprint to power the operation of such platforms.

The operator of a platform has two different options to power all the local machinery: generate electricity on site with gas turbines that drive generators or get electricity from shore via subsea cables. While it seems natural to use the gas produced at the platform to run local gas turbines, in the majority of cases this is not the most economic solution.

1 Key components of a VSC-based HVDC system



Gas turbines (GTs) are essentially jet engines that extract energy from a flow of hot gas produced by the combustion of gas or fuel oil. Shaft power generated in this way drives generators to produce electricity. The process of producing electricity involves combustion, compression, heat transfer and spinning, resulting in the need for equipment that, besides consuming a great deal of fuel, requires considerable operation and maintenance (O&M) efforts.

A platform with a generating capacity of 100 MW would typically release over 500,000 tons of CO_2 per year.

GTs deployed offshore are mostly simple-cycle types due to weight and space constraints on platforms. Simple-cycle GTs have remarkably low energy conversion efficiencies, particularly when operated at less than full capacity, as is often the case. Best operating efficiency of GT generation is in the range of only 25 to 30 percent. Considering the ideal fuel to electrical energy conversion ratio for standard natural gas of 10.8 kWh/m^3, burning one standard cubic meter of natural gas produces just about 3 kWh of electricity and at the same time releases about 2 kg of CO_2. A platform with a generating capacity of 100 MW would typically release over 500,000 tons of CO_2 per year, combined with the emission of about 300 tons of nitrogen oxide (NO_x), a gas corrosive to both the environment and to people's health.

O&M work is proportional to the number of GTs onboard. It is not uncommon that a platform consuming 100 MW would have five or six GTs onboard given the redundancy requirement and individual applications involving direct GT drives.

AC cables transmitting power to offshore installations are a proven technology, typically supplying to platforms at distances of tens of kilometers. For longer distances, AC cable transmission poses challenges as a number of issues inherent to AC systems become important. Coaxial cables form distributed capacitance increasing with cable length. In AC systems, cable capacitance generates reactive power, which should be compensated by midpoint reactive power compensators or Static Var Compensators (SVCs), for example.

Dynamic issues associated with long-distance AC cables need to be evaluated and mitigated as well. For example, the presence of large cable capacitance in series with transformer magnetization reactance could lead to ferroresonance during line energizing and to possible failure. Also, momentary voltage dips due to onshore grid disturbances amplify while propagating along long cables, possibly tripping sensitive offshore equipment.

DC cable transmission fits best to connect offshore platforms.

DC cable transmission systems, on the other hand, are generally immune from the drawbacks associated with long-distance AC cables. In fact, voltage source converter (VSC)-based high-voltage direct current (HVDC) systems are designed to transmit large amounts of power over long cable distances. A major cable distance limitation was thus lifted upon the arrival

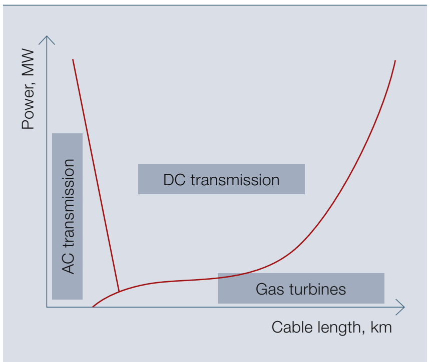
2 HVDC Light module on Statoil's Troll-A platform

of VSC-based HVDC transmission to offshore applications [1, 2].

The main difference between DC and AC transmission is the presence of an AC-to-DC converter that rectifies onshore grid AC power to DC power for the purpose of transmission and the presence of a DC-to-AC converter at the consumer end that synthesizes DC power back into AC power 1. While the converters increase the cost of the DC system, the number of required cables is reduced from three for the AC system to two for the DC system. This reduction, combined with the reduced DC cable size due to inherently higher utilization efficiency, results in cable cost savings that could more than compensate for the converter cost as the cable distances increase.

HVDC Light® is a cable transmission system based on ABB's VSC-based HVDC technology. The system, initially developed for land-based applications, went into operation in 1997 on the island of Gotland in Sweden, connecting wind generators in the south to the island's grid in the north. Since then, eight such systems have been installed worldwide for land-based applications, totaling almost 1,200 MW and 500 km. The first offshore version of HVDC Light® went into operation in the North Sea in 2005 at Statoil's giant Troll-A gas platform 2. The next HVDC Light® footprint is scheduled to take place at BP's Valhall field, also in the North Sea, with operation scheduled for 2009.

3 CAPEX – "Windows of opportunity"



DC transmission offers a broad "window of opportunities" for CAPEX savings.

HVDC Light® electrical converters are based on Insulated Gate Bipolar Transistor (IGBT) power semiconductors with switching frequencies of up to 2,000 Hz in synthesizing the sinusoidal AC output. The maintenance requirement is small compared with a single GT, as it is determined by conventional equipment such as AC breakers and cooling systems.

The optimal solution

When selecting the energy supply for a platform the operator has to evaluate a number of different criteria:

- Greenfield or brownfield upgrade or extension
- Application of the energy on the platform
- Local regulations
- Installation cost
- Operational cost

Field development

A new field development allows for a fresh approach with little or no demolition or removal expenditures for existing equipment. Troll-A HVDC Light® is an excellent example where the need for pre-compression of gas for pipeline transportation arose due to a drop in reservoir pressure over past production years [3].

A field redevelopment may as well necessitate additional power and may or may not require demolition work to remove existing generation equipment. Valhall HVDC Light® was part of a redevelopment project where the field operator, BP, decided to remove the existing GT and rely solely on power from shore (PFS) with the power supply capacity increased to the required value [4].

A third type of field development involves electrification of an existing platform or of a cluster of fields.

Applications

If a compressor is driven by a variable-speed drive to achieve targeted process performance, an HVDC energy supply, together with a high-voltage motor, would be the preferred solution, as was the case for the Troll-A pre-compression project [5].

4 Life-cycle OPEX parameters

OPEX parameters	NCS	Average	
Electricity wholesale price	46.7	66.7	$/MWh
Fuel sales value	0.24	0.24	$/Sm³
HVDC Light converter losses	4 %	4 %	
HVDC Light cable losses	4–6 %	4–6 %	
Fuel to electricity conversion at 100% efficiency	10.8	10.8	KWh/Sm³
GT turbine efficiency	40 %	30 %	
Released CO_2 at 100 % efficiency	0.21	0.21	
CO_2 tax or trade value	56.3	16.7	$/ton
Released rate of NO_x	0.4	0.4	kg/kWh
NO_x tax (over 20 year horizon)	7.5	2.5	$/kg
GT O&M costs/yr per 25 MW unit (+ WHR + ST in NCS)	2.5	1.7	M $/year
HVDC light system O&M (all sizes)	0.7	0.7	M $/year
Analysis period	20	20	years
Interest rates – net present value	7 %	7 %	

An application may require the direct online start of motors (eg, BP's Valhall). This can be simply factored into the design of a VSC-based HVDC system. However, for GT and AC PFS solutions, devices such as soft-starters would be needed on the platform.

Local regulations

Regulations play an important role in the deployment of efficient, environmentally friendly and safe equipment offshore. In Norway, efficiency-boosting equipment such as waste heat recovery (WHR) units and steam turbine generators (ST) are mandatory in new GT capacities offshore. The required efficiency improvement for simple-cycle GTs from typically 25 to 30 percent to around 40 percent reduces fuel consumption and taxable greenhouse gas (GHG) emissions while adding to O&M costs. WHR and ST would also add to initial capital expenditures and to space and weight requirements on a platform. Such regulations clearly have a favorable influence in consideration of PFS.

Initial investment CAPEX

With a given set of development, application and local regulations, the estimation of initial investment depends on the primary system factors, meaning rated MW and installed kilometers of cable. Together they form a pattern for the so-called "windows of opportunity" 3.

For a given transmission distance, the capital expenditure (CAPEX) transition between DC PFS and GT is governed largely by the MW power capacity to be installed. With increasing power requirements, the DC PFS option becomes more favorable. While HVDC Light® is simply sized up to cover just about any given megawatts (up to 1,000 MW), GT units multiply in number to achieve the required level. In addition, the gas turbine's O&M expenditures increase with the number of GTs but remain at about the same low level for HVDC Light® [6, 7].

Life-cycle OPEX savings are significant with power from shore.

Longer distances favor the DC solution when additional converter costs can be balanced by lower cable costs.

Economic evaluation of competing power supply solutions requires intimate knowledge of the capital and other initial expenditures and of the parameters influencing life-cycle operating expenditures (LC OPEX) specific to a given project. These costs have to be analyzed on a case-by-case basis.

Unlike CAPEX data, which is strictly proprietary in nature, OPEX data are widely available in public data sources. Based on this large set of published data, a comparison of LC OPEX can be made for GT- and PFS-based solutions. The comparison is made along three sets of parameters: 25 MW/50 km, 100 MW/100 km and 250 MW/300 km. Each of these cases is analyzed for Norway and "Average"; Average refers to regions such as the European Union where GHG emissions or efficiency-related regulations are more moderate and the cost of electricity is higher than in Norway.

The major components of LC OPEX are costs of fuel and offshore O&M manpower. Additional costs related to GHG, in form of either local taxation as in Norway or trading value as in the European Union. LC OPEX forms a substantial part of the total cost and has to be included in any life-cycle cost calculations for power systems that are under consideration.

4 lists key published OPEX parameter values, associated with the two regional scenarios for GT- and PFS-based solutions. Since differences between AC and DC cable systems are minor from an OPEX point of view, the following calculations use HVDC Light® solutions to represent AC and DC PFS-based options. The indicated electricity prices are expected wholesale prices, and the CO_2 trade value

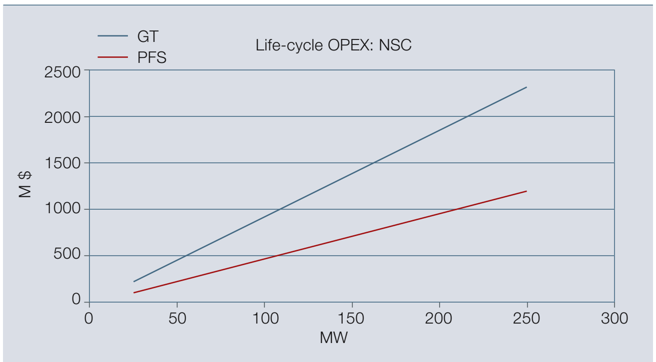
5 Life-cycle OPEX costs: 100 MW, 100 km, Norway

Life-cycle OPEX costs – NCS 100MW, 100km:	GT	PFS
	M $	M $
NG fuel or electricity costs	552	505
CO_2 taxation	294	0
NO_x taxation	30	0
O & M costs	113	8
Total life-cycle OPEX	988	513

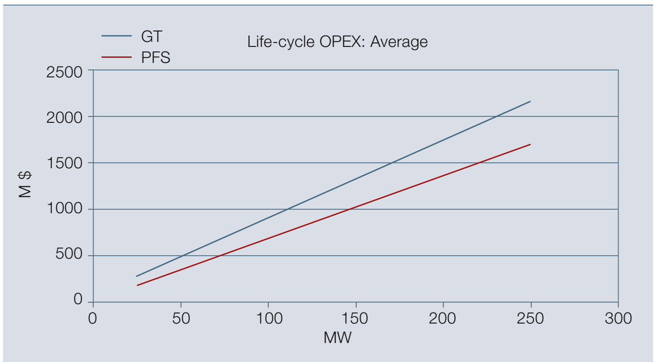
6 Life-cycle OPEX costs: 100 MW, 100 km, "Average"

Life-cycle OPEX costs – Average, 100MW, 100km:	GT	PFS
	M $	M $
NG fuel or electricity costs	736	722
CO_2 taxation	116	0
NO_x taxation	10	0
O & M costs	76	8
Total life-cycle OPEX	937	729

7 Life-cycle OPEX for Norway: GT versus PFS



8 Life-cycle OPEX for "Average" regions: GT versus PFS



for Average regions is based on a 20-year horizon.

HVDC Light® is a cable transmission system based on ABB's VSC-based HVDC technology. The system, initially developed for land-based applications, went into operation in 1997 on the island of Gotland in Sweden, connecting wind generators in the south to the island's grid in the north.

5 and 6 provide estimated net present values of life-cycle OPEX for Norway (NCS) and Average for 100 MW and 100 km. LC-OPEX amounts are large and clearly form the dominant quotient of total life cycle cost (CAPEX + OPEX), particularly for new development or redevelopment projects.

LC OPEX as a function of power for Norway and Average regions is presented in 7 and 8.

The savings in LC OPEX when using PFS instead of GT is significant for all considered cases 9. The savings in offshore emissions of greenhouse gases associated with GT-based generation are also remarkable when using PFS solutions 10 11.

PFS: an attractive alternative

The examples given clearly show that a power supply to platforms from mainland via cables offers highly economic and environmentally friendly solutions that increase operational safety at the same time. While individual evaluations are needed for each project, the typical cases presented here give enough indication to seriously consider PFS solutions for greenfield and brownfield installations. ABB's HVDC Light® systems have demonstrated the advantages, and it can be expected that more platforms will be equipped with PFS solutions in the future.

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9 Live-cycle OPEX savings with PFS for all six cases

Live-cycle OPEX savings with PFS	NCS M M $	Average M $
250 MW, 50 km	114	48
100 MW, 100 km	476	208
250 MW, 300 km	1189	514

10 Annual CO_2 reduction on platform with PFS

Yearly CO_2 reduction on platform	NCS ton	Average ton
250 MW, 50 km	114,975	153,300
100 MW, 100 km	459,900	613,200
250 MW, 300 km	1,149,750	1,533,000

11 Annual NO_x reduction on platform with PFS

Yearly NO_x reduction on platform	NCS ton	Average ton
250 MW, 50 km	88	88
100 MW, 100 km	350	350
250 MW, 300 km	876	876

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Starting the boiler

Startup optimization for steam boilers in E.ON power plants

Rüdiger Franke, Bernd Weidmann

There is a proverb saying that a watched pot never boils. When it comes to bigger pots however – such as boilers in power plants – looking away is certainly not the best control strategy in starting them up.

Optimization efforts in power plants often focus on extracting as much usable energy out of the fuel as possible during normal operation. There is another important way to improve efficiency, however, and this lies in optimizing startup procedures. This is all the more important as the fuel used at start-up is often of higher grade and more costly than that used in normal operation.

BoilerMax is a predictive controller used to minimize start-up costs. Besides fuel costs, it takes into account such constraints as maximum permissible loads of critical components and flow rates.

In the course of the last two years, BoilerMax has been installed in several power plants of the energy company, E.ON where it has typically achieved savings of 10 to 20 percent of the costs for fuel and auxiliary power required for a startup.

Extraction and generation

Over the last two years, BoilerMax has been installed in several E.ON power plants and integrated with several control systems. In the 622 MW Staudinger 4 gas-fired unit [1] and in the 900 MW Heyden 4 coal-fired unit, it works with a Procontrol P unit control system. In the 420 MW Ingolstadt 4 oil-fired unit and the 450 MW Zolling 5 coal-fired unit, BoilerMax has been integrated into a new 800xA control system, installed in the course of a turbine retrofit project.

The operating principle of BoilerMax

BoilerMax especially takes into account fuel costs and thermal stress in critical thick-walled components and uses this data to compute optimal setpoints for the fuel supply and the operation of the high pressure (HP) bypass station (the high pressure turbine can be bypassed in the steam circuit during startup to permit a faster build-up of boiler pressure).

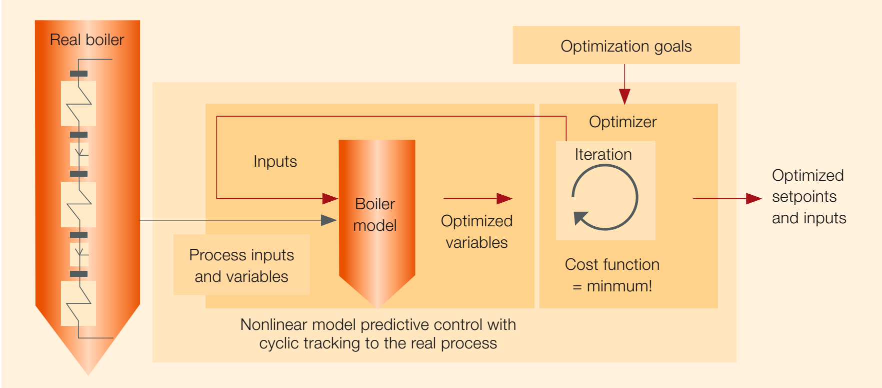
The functional principle of BoilerMax is shown in 1. Measured values are used to calibrate a physical unit model. Based on this nonlinear model, BoilerMax optimizes the remainder of the startup procedure. The resulting startup curves computed on-line are then integrated into the existing unit control concept, where they are used as correction setpoints.

BoilerMax's prediction horizon is 60 to 90 minutes, covering the entire duration of the boiler startup – up to the point where the turbine is rolled on steam. This way, the most cost-efficient overall operating mode can be computed. The predicted data is updated every one to two minutes, enabling an adequate response to disturbance conditions.

The startup costs to be minimized are in the area of fuel, auxiliary power and auxiliary steam, from “fire on” to “generator on-line” or “HP-bypass closed.”

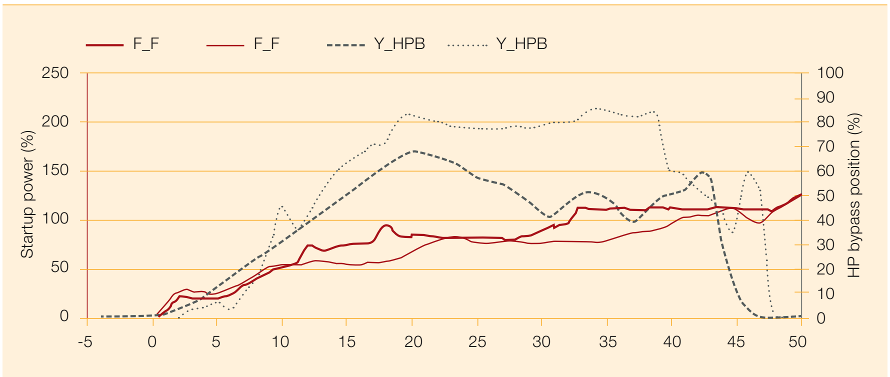
Independently of the cost savings realized, the model-based multi-variable controller also enables a predictive integration of thermal stress data into the closed control loop. The level of flexibility, eg, covering different

1 Functional principle of BoilerMax

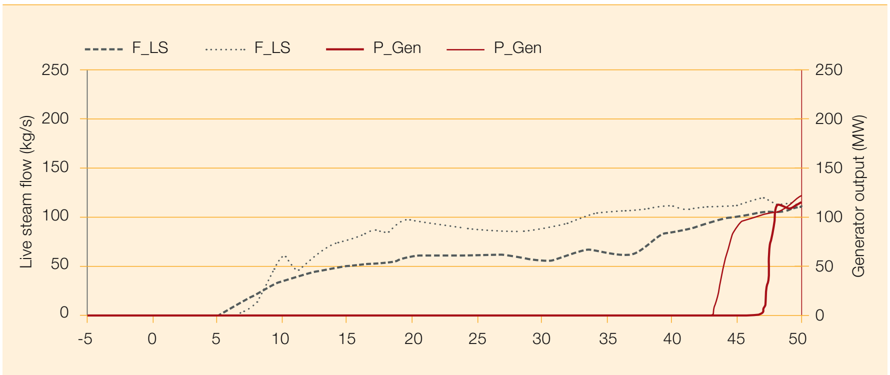


2 Comparison of two startups with BoilerMax (bold lines) and without BoilerMax (thin lines) in the Ingolstadt oil-fired power plant, unit 4

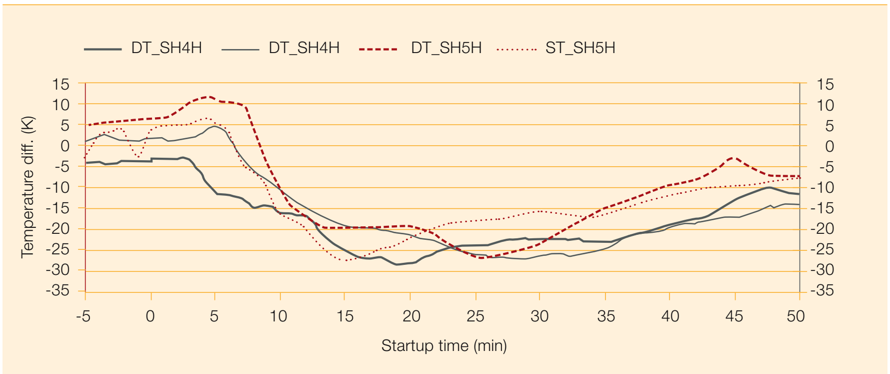
a Fuel quantity (F_F) and the HP bypass position (Y_HPB)



b Live steam flow (F_LS) and the generator output (P_Gen)



c Temperature differentials (DT_SH4H) and (DT_SH5H) occurring in HP headers of the two last superheater levels



downtimes, is improved as the physical model is continually adjusted to match the current state of the plant. Moreover, the startup can be adapted to changes in basic conditions, such as different fuel costs or maximum permissible loads, by modifying the target function and optimization constraints, respectively.

Operational experience

Reducing fuel consumption

Thanks to the predictive startup optimization, it is often possible to run a startup using less fuel, while maintaining the usual startup time and stress loading on critical thick-walled components. 2 shows a comparison of two startup procedures in Ingolstadt power plant's unit 4. The diagrams clearly show that it was possible to run a similar boiler startup while realizing an approximate 20 percent reduction of fuel consumption. Such fuel savings are possible because the steam flow used for starting-up can be decreased by simultaneous and coordinated reduction of the opening of the HP bypass station. In addition, the startup time is slightly reduced.

BoilerMax takes into account fuel costs and thermal stress in critical thick-walled components and uses this data to compute optimal setpoints.

With a higher level of automation, achieved by the optimized startup procedures, startup procedures generally become more consistent. 3 represents the startup costs as a function of the duration of the preceding standstill. The spread of startup costs is most visibly reduced in the case of frequent brief standstills, with numerous startup runs taking place under similar conditions. The optimized startup costs achieved with BoilerMax are at the lower end of the cost range that is characteristic of operations without BoilerMax. On average, the startup optimization resulted in a 19 percent reduction of the startup costs.

Following brief standstills, startup costs are high because of the high live-steam temperature that has to be built up on account of the high initial temperature in the turbine. Startup costs also rise after long standstills, however, because of the lower starting temperature of the boiler.

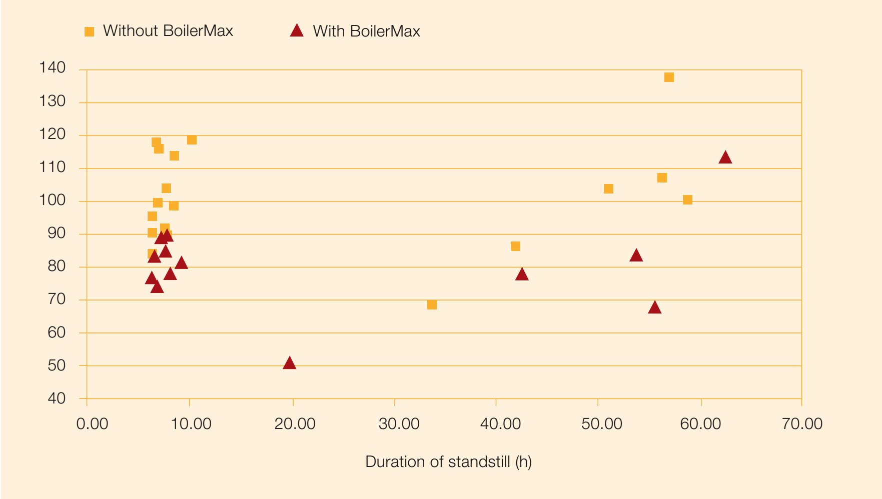
The reduction in fuel consumption resulting from Boilermax's optimization, as well as lower steam production and, in some cases, a slower pressure build-up, may give operators the impression that the entire startup procedure is somehow dragging on. However, it is important to consider that, during boiler startup, the target setpoints for steam flow and pressure must be attained only when the turbine is actually about to be rolled on steam. The predictive optimization concept makes full use of this fact.

The startup times achieved in Unit 4 of the Staudinger power plant are shown in 4. These curves show that BoilerMax did not prolong startup times.

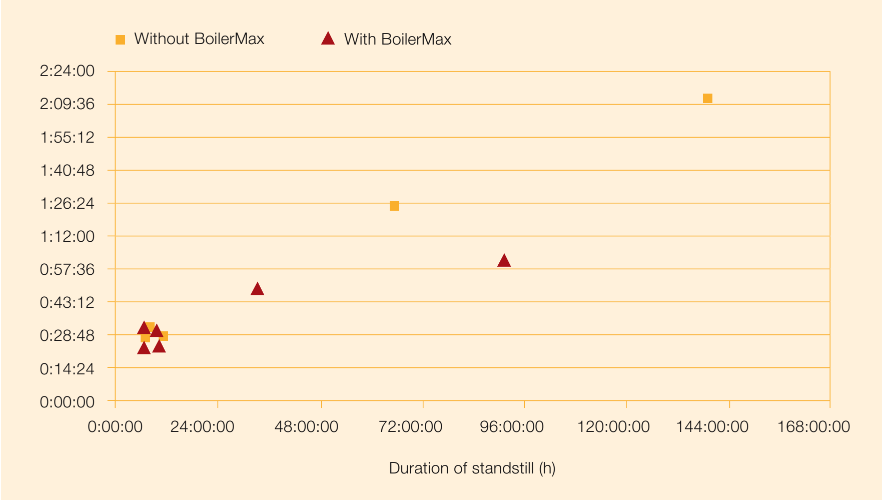
Reducing startup times

The startup times can generally be reduced if an intensification of the heat-up process is admissible and higher heat-up stress is acceptable. Applying predictive startup optimization in order to reduce startup times is advisable if the permissible heat-up stress

3 Startup costs as a function of the duration of the standstill in the Ingolstadt oil-fired power plant, unit 4, with and without BoilerMax



4 Startup times as a function of the standstills in the Staudinger 4 gas-fired unit, indicated for ten startups over a period of one month



Extraction and generation

margin is not fully exploited, or if the load is distributed unevenly during startup.

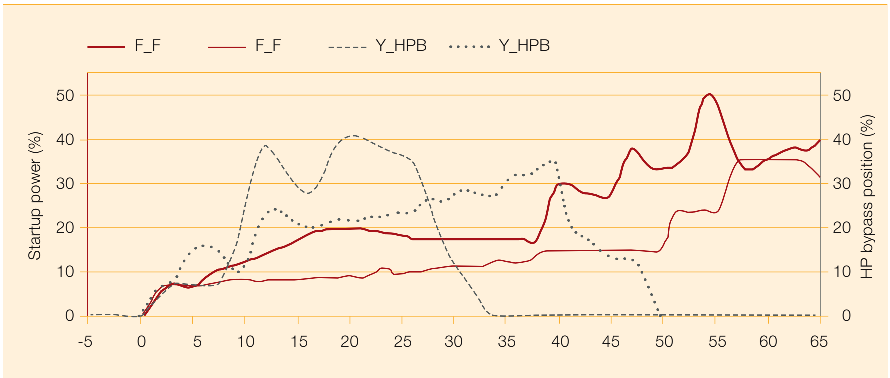
A comparison of two startup procedures in the Zolling coal-fired power plant is shown in 5. Without BoilerMax, the margins for heat-up stress were not fully exploited before the 48th minute. The maximum temperature differential in the HP outlet headers was about 20 K, whereas the admissible limit was about 30 K.

Only during subsequent loading of the turbine, was the maximum heat-up stress reached at around minute 60.

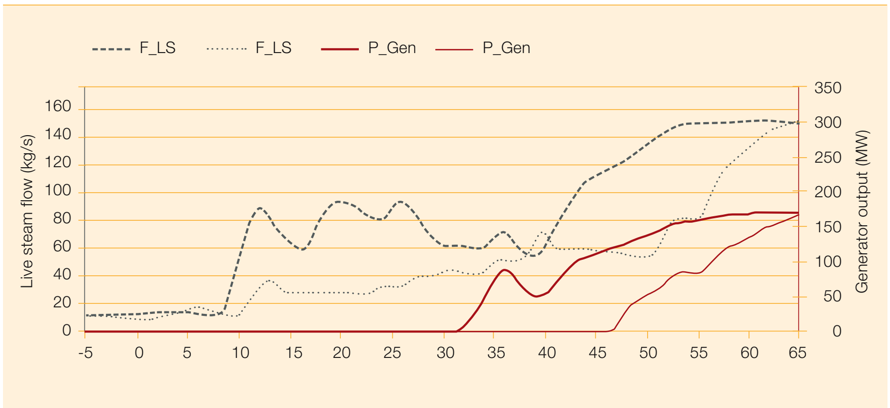
The ΔT limit used by BoilerMax is a function of the pressure which is generally specified by the boiler supplier. As an option, the limits can be recalculated during the physical modeling of the boiler and agreed in consultation with the power plant owner.

5 Comparison of two startup procedures with BoilerMax (bold lines) and without BoilerMax (thin lines) in the Zolling coal-fired power plant

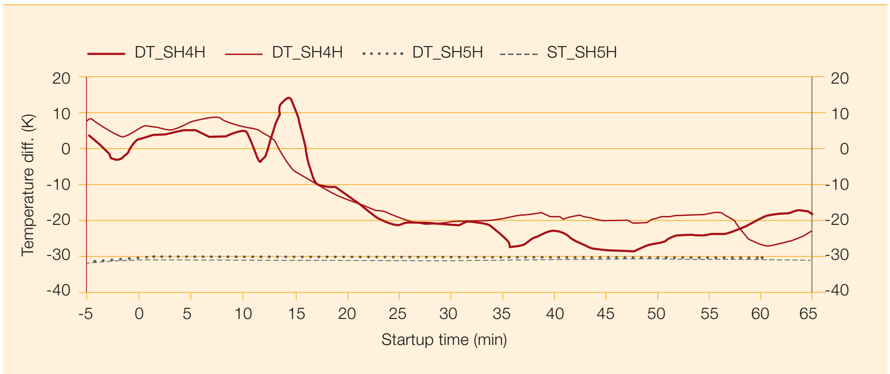
a Fuel quantity (F_F) and the HP bypass position (Y_HPB)



b Live steam flow (F_LS) and the generator output (P_Gen)



c Temperature differentials (DT_SH5H) [K] as well as the associated limit values (DT_SH5H_min) [K] occurring in the HP outlet headers



As shown in 5, predictive startup permitted a better utilization of the margin as early as minute 35. This was achieved by increasing the fuel supply at a higher rate from the beginning, while at the same time opening the HP-bypass station to a greater extent. This reduced the startup time by 33 percent. The amount of heavy fuel oil needed for starting-up was reduced by about 6 percent. Since a shorter startup time is accompanied by a lower demand for auxiliary power (light oil and electrical auxiliary power), the total startup costs were diminished by about 11 percent. Moreover, there is a high savings potential in coal-fired plants when the shift from startup fuel to coal firing can be achieved earlier. To achieve this, it is important to be able to start up using a high overall quantity of fuel.

On average, the startup optimization resulted in a 19 percent reduction of the startup costs.

With predictive startup optimization, the amount of fuel is not necessarily increased monotonically, but can be cut back after an initial excess supply.

Operating and monitoring

The operating screen used in the Zolling plant is shown in 6. The left and the upper parts show the process parameters that are especially relevant during startups. The lower right area is used for the actual BoilerMax application. The setpoint settings for fuel and HP bypass control, as computed by BoilerMax, are shown along with the actual values.

The process values shown in this display primarily cover the live-steam parameters and temperature differentials in thick-walled components. In order to avoid cluttering of the display, the ΔT readings are shown in graphical form (bar charts). Alphanumerical representation is limited to the maximum values for each superheater level and the associated limit values.

Visualizing ΔT limits is especially important, as these values are used by

BoilerMax in a closed control-loop for defining the fuel and HP-bypass control actions. It is therefore important to present information on the current heat-up stress and the available margins so that the operator will be able to correctly understand the setpoints computed by BoilerMax.

With a new 800xA process control system, the predictive data computed on-line during each startup, is available directly at the operator's workplace. Predicted startup data can be viewed in a regular operating trend that represents the values to be expected in the future.

Integration into the unit control system

Predicting and optimizing the startup procedures of a boiler on the basis of a physical model involves elaborate numerical processing. BoilerMax is therefore implemented on a high-performance PC that is linked to the unit control system via a signal interface.

From a software point of view, BoilerMax has been implemented by ABB using the Dynamic Optimization system extension for the company's Industrial IT Extended Automation System 800xA. This assures a high degree of transparency and flexibility regarding its capability of being integrated into the operational instrumentation and control equipment. Two implementation scenarios are shown in 7.

In the first case, the BoilerMax PC can be implemented independently and be connected directly to a control cabinet. Viewing and operating occur through regular operating and monitoring stations. In plants where the operating and monitoring stations are implemented as component parts of the System 800xA, the PC on which BoilerMax is running can be integrated as an application server. This provides a special advantage: all parameter settings and calculation results, including the predicted process values, can be made visible and be integrated into the display without additional effort. Furthermore, this facilitates staff familiarization with the BoilerMax solution and this PC can be included in the regular maintenance routines for the System 800xA.

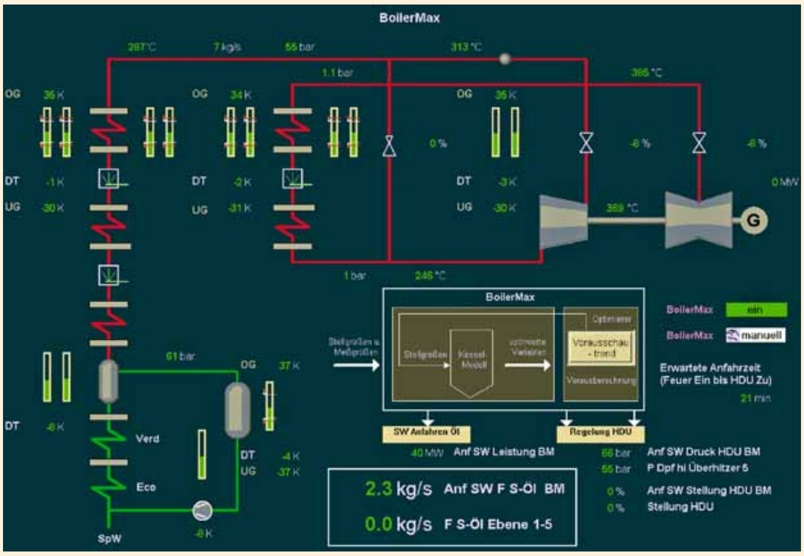
In the Ingolstadt and Zolling power plants, the BoilerMax PC has been integrated with the 800xA operating system which was installed during a turbine retrofit project. In the Staudinger unit 4 and Heyden power plants, the BoilerMax PC is linked to the Procontrol P process control system via a serial interface.

> Predicting and optimizing the startup procedures of a boiler on the basis of a physical model involves elaborate numerical processing.

The unit model used for startup optimization is adjusted on-line by incorporating 100 to 200 measured values. In general, these signals are connected to the process control system as analog signals. As an alternative, a ProfiBus connection has been established between the newly installed turbine controller and the existing unit control system in the Ingolstadt plant. The main advantage of this digital bus coupling is a higher flexibility, because individual signals can additionally be integrated, requiring little extra work. Longer signal transfer times might be viewed as a possible disadvantage; in the Ingolstadt installation, however, no problems arose in this regard. The optimization results are fed back into the control system using approximately ten signals. They are integrated into the existing control concept in the form of setpoint corrections for fuel and HP bypass control.

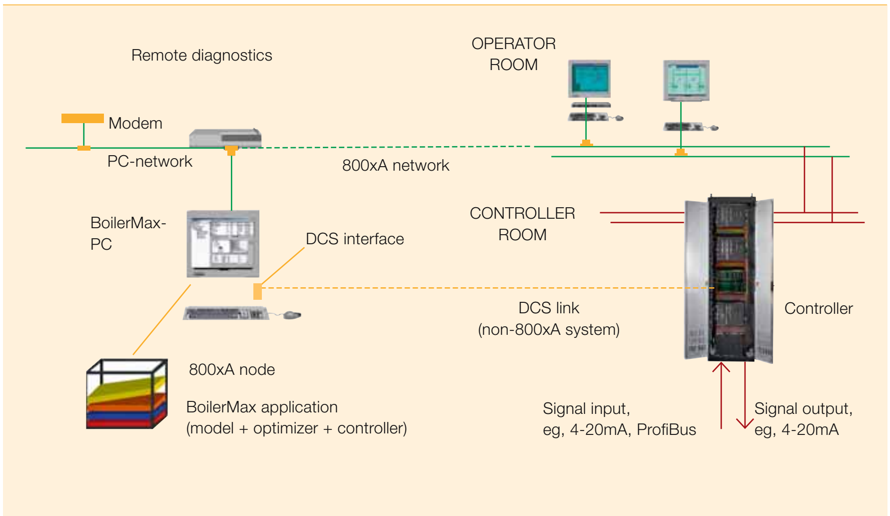
Depending on the given circumstances, this integration may affect different system levels. In the Zolling power plant, the optimized setpoint for startup fuel supply is only visualized and then applied manually by the operating staff. In Unit 4 of the Staudinger power plant, both fuel and HP bypass control are automatically performed by BoilerMax. At present, however, BoilerMax needs to be activated before each startup. In the Ingolstadt power plant, BoilerMax is activated automatically. The more automated the integration of BoilerMax is, the higher the achievable savings potentials: A sustained improvement of cost-efficiency will ultimately be achieved only by repeated use of the optimization function. A higher degree of automation, however, poses higher demands on the robustness of the startup optimization in view of, eg, automatic detection and handling of disturbances.

6 BoilerMax operating screen used in the Zolling power plant. Because of the high computing power required, BoilerMax is run on a PC that is configured as an application server.



Extraction and generation

7 Integration of the BoilerMax PC
(Secondary control room, Control room, DCS interface, I&C room, Control cabinet, Optimizer, Controller, Signal input, ProfiBus, Signal output)



The implementation of the online optimization using the Dynamic Optimization system extension provides for openness of the advanced control solution through a high level of integration with the Extended Automation System 800xA [4].

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Successful implementation

The savings realized through online optimization are generally within 10 to 20 percent of the normal costs of fuel and auxiliary power for each power plant startup. The modifications of the startup mode depend on the specific requirements of each power plant.

In the Staudinger unit 4 and Ingolstadt unit 4 power plants, the savings were brought about by a reduction of the fuel consumption and a coordinated lower live steam flow during boiler startup. Both startup times and stress loading of critical thick-walled components remained approximately the same.

BoilerMax was presented at VGB's 2004 congress on "Electrical, Control and Information Technology in Power Plants" together with first practical results from its pilot application in the Weiher III power plant [1]. Results obtained in the Staudinger 4 power plant, where BoilerMax was installed together with a new control system, were presented in [2]. More details about the control and optimization algorithm can be found in [3].

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To the last drop

How wireless communication supports the lifetime extension of oil and gas production

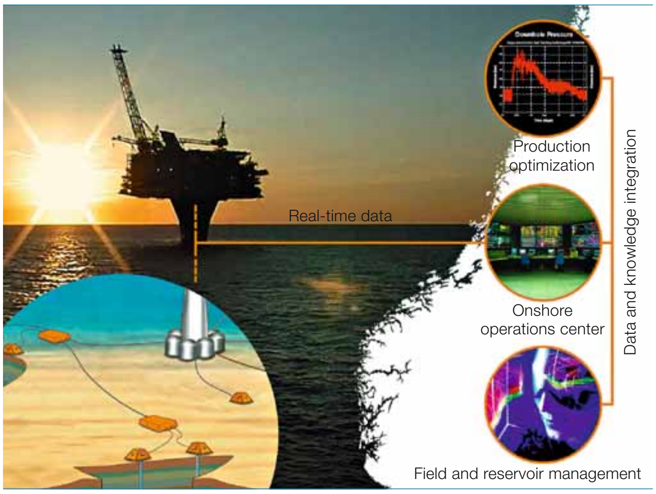
Egil Birkemoe, Jan-Erik Frey, Stefan Svensson, Paula Doyle

Cost efficient exploitation of primary energy is one of the major challenges of today's society. This is especially vital when oil and gas fields reach the limits of their reservoirs and start to "dry out". Oil and gas production companies then try to use the installed equipment as long as possible in order to avoid costly new installations. Every improvement in operational efficiency directly pays off in such a situation.

Many of the oil and gas installations in the North Sea were built in the 1970s, and are now entering the tail production phase. Few new large greenfield projects are currently planned in the Norwegian and British sector, hence the industry's focus is shifting to brownfield projects. As a consequence of this shift critical issues have to be addressed:

- In the tail phase of production efficient operation is vital to prolong the life of the fields.
- The aging equipment requires more maintenance.
- Condition-based maintenance aimed at the reduction of operational cost is crucial.

1 Major elements of a production site in the North Sea



Integrated operations

To get a grip on this huge task of managing thousands of devices, systems and installations, an extensive use of online data for both increased production and efficient operation and maintenance is the way forward. Within the upstream oil and gas industry, many initiatives along these lines have been started, known as Integrated Operations, e-Field, Field of the Future, Smart Fields etc. The potential for Integrated Operations on the Norwegian continental shelf was estimated at 250 billion NOK in 2006 in a report issued by the oil industries association in Norway [1].

Power consumption has a dramatic impact on the life time of the sensors or on the feasibility of a self-powered solution

ABB is an active player, collaborating with oil companies, other vendors, and academia to realize the Integrated Operations concept **Factbox**.

The challenge of data acquisition

Upstream oil and gas production plants consist basically of a production plant taking hydrocarbons from a reservoir in the ground to an export line with processed oil and gas. In the North Sea, the production plant is normally located offshore. It resides on a steel jacket, concrete structure or a floating unit depending on the sea depth and technology available at the time of construction. The latest developments also include sub sea processing facilities. **1**

In order to be able to use a reliable and secure bandwidth to collect the required data in this challenging environment, oil companies have invested in a fiber-optic network in the North Sea. Further enabling technologies to support extensive data transfer are under development: fiber optic networks in the wells, wireless communication around the platforms (support vessels etc) and throughout the plant, at the top side facility or between platforms.

Traditionally installation of sensors for online data collection requires wires. For new installations, wireless sensors can save on cabling costs. When it comes to retrofitting wiring, this is even more costly and often impossible on a large scale as it requires installation personnel on site. Furthermore, limited bed and transport capacity on the oil rig is often a restraining factor. In order to wire the sensors, it may also be necessary to set up scaffolding, remove insulation and traverse bulkheads and explosion and fire-protected compartments, further adding to costs.

Factbox Collaborating for success

ABB is delivering products within condition monitoring, performance monitoring and production optimization to many different upstream installations.

ABB was selected as the industrial research and development partner by StatoilHydro within the area of operations and maintenance, heading a consortium known as TAIL Integrated Operations including AkerKværner, SKF and IBM [2].

Another major R&D program is a wireless vibration sensor development supported by BP and StatoilHydro. ABB is heading the consortium which also includes SINTEF and SKF.

The two above projects are supported by the Norwegian Research council under the Petromaks program.

Wireless sensor networks

In mature offshore fields, the use a low-cost wireless sensor network (WSN) presents a major advantage when it comes to feeding measurement and communication equipment data to central units. The WSN can be retrofitted on offshore platforms that have hundreds of pumps, fans, and other motor driven devices requiring permanent maintenance.

The technical challenges of a WSN in this environment are significant, however. The WSN's principal requirements include:

- Reliability of the communication in harsh environments
- Predictable latency, ie, the delay and determinism of the communication
- Low power consumption of the sensor node and communication
- Security, which ranges from message confidentiality (end-to-end encryption), message integrity checking, authentication and secure procedures for network access
- Coexistence with other equipment and competing wireless systems

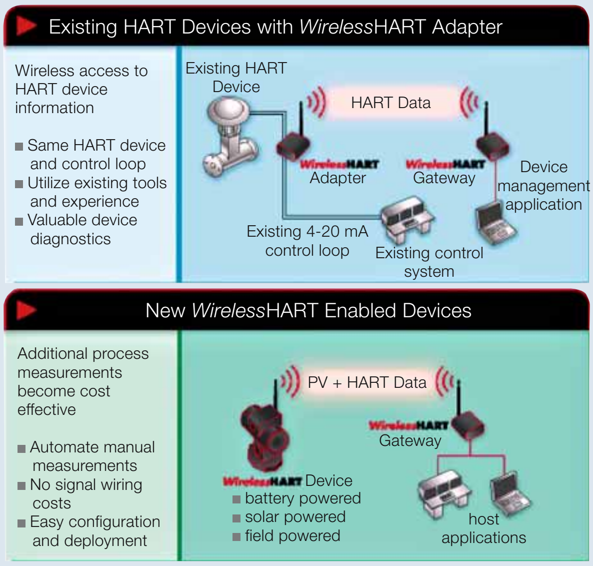
For condition monitoring applications, which typically have a lower update rate, the latency is less important whereas reliability, security and power consumption remain vital.

Power consumption has a dramatic impact on the life time of the sensors (if battery operated) or on the feasibility of a self-powered solution (eg, harvesting energy from heat or vibration sources in the surrounding environment). To reduce energy consumption, the node needs to be dormant as much as possible and, when active, send as few bits as possible [3].

In addition to coping with the extensive steel structures on a platform, the WSN also has to co-exist with other typical offshore systems that potentially disrupt the safe exchange of data. Among those are large power generators, UHF/VHF radios, radars, safety and automation systems, and more increasingly also WLAN[1].

Spectral analysis on such offshore locations, however, do not indicate any significant background noise in the 2.4 GHz frequency band – the band that is targeted by many of the existing and upcoming solutions for WSN. On the other hand, future deployments of WLAN (IEEE 802.11) and WiMax (IEEE 802.16) systems may change this picture [6]. For future WSN solutions it is mandatory to be able to co-exist with WLAN, the most wide spread technology in this industry.

2 The use of WirelessHART in existing and new applications



In search for WSN standards

One of the most significant concerns within the automation industry in general has been the lack of suitable standards to fulfill all of the demands mentioned above. This picture is gradually changing with the release of the WirelessHART™ Standard [4] in September 2007. ABB has played an active role in the definition of the WirelessHART specification[2].

Another emerging standard that looks promising for industrial applications is ISA100 – Wireless Systems for Industrial Automation [5]. ISA100 has a much larger scope than WirelessHART and aims to address a whole family of standards:

- Process automation (ISA100.11a)
- Factory automation (discrete focus)
- Transmission and distribution (long distance focus)
- RFID (industrial tagging focus)

WSN has to co-exist with other typical offshore systems that potentially disrupt the safe exchange of data.

Since WirelessHART already provides a good solution for process automation applications, there is an ongoing discussion about how WirelessHART could be best integrated with ISA100.11a so that co-existence and interoperability is ensured.

The advantages of *Wireless*HART

The development of *Wireless*HART was based on the same principles that governed the development of wired HART: The communication and application levels are both part of the solution and the protocol itself is kept as simple as possible.

This similarity of the standard permits an improved use of existing instrumentation in off-shore installations. In fact, many off-shore installations are already equipped with HART instruments. These cannot, however, be used to their full extent due to the fact that legacy DCS systems are blocking the HART signals and hindering any HART communication between device and operator station.

A simple *Wireless*HART adapter at the existing instrument can provide the missing additional functionality and boost the performance of the entire control system. Condition monitoring, urgently needed in tail operation is then possible via the wireless channel. **2**

*Wireless*HART is based on the 802.15.4 standard which provides the lower layer levels of the communication stack. The IEEE standard focuses on low-cost, low-speed ubiquitous communication between devices with little to no underlying infrastructure. Using 802.15.4 as basis ensures a reliable radio technology and numerous suppliers of technology.

The 802.15.4 radio is specified to provide a minimum of 10-meter communications range and a transfer rate of 250 kbps. With more sensitive radios and power amplifiers, however, WirelessHART should be capable of reaching distances up to 200 meters (line-of-sight).

Wired HART already has an installed base of over 24 million devices as of 2007. To make best use of the tools and software already available it makes sense to build on that installed base.

*Wireless*HART was developed to support the following applications:

- Field device troubleshooting
- Device status and diagnostic monitoring
- Critical data monitoring with more strict performance requirements

Footnote

[1] WLAN: Wireless Local Area Network

[2] See also "Wirelss – the future for instrumentation," *ABB Review* 4/2007,16–17.

- Supervisory process control
- Calibration
- Commissioning

Meshed network concept

Utmost reliability of the *Wireless*HART network is achieved through means of a meshed network where all nodes are able to route messages from a neighboring device, efficiently providing an additional data path.

The ability to avoid disturbances when these occur by shifting from one frequency to another is also adding to the overall reliability of the network. The frequency hopping is realized through a TDMA (time division multiple access) scheme, which makes sure that nodes are communicating on different frequencies at different points in time.

The system provides alternative communication paths so that communication can continue when the original path is blocked by a physical obstruction or by interference. As every device should aim to have at least two routes to the receiver, one of these can instantaneously come into use when the original one is blocked.

Low power consumption

TDMA guarantees a reserved time slot for each link between communicating devices. This ensures low power consumption as the nodes are synchronized and only need to be active during the appropriate time-slots and for re-synchronization.

Security

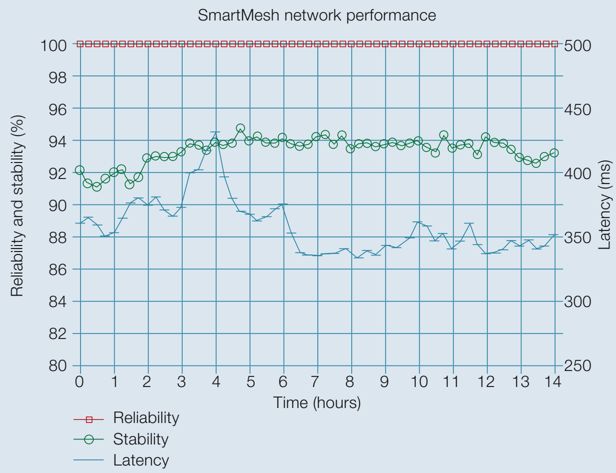
The 128 bit AES[3] encryption defined in the 802.15.4 standard is widely accepted as state of the art. Although more advanced security solutions (as elliptic curve cryptography) might be required in the future, AES fully satisfies today's requirements bearing in mind that low power is one of the fundamental goals of the communication solution, and complex security solutions add to the power requirements. Distributed keys are used to allow only authorized devices to enter the network; this in itself helps guarantee the authenticity of data.

Coexistence

Because *Wireless*HART uses the media access control protocol defined by the IEEE standard, harmonic coexistence with other networks using the same IEEE standard (eg, ZigBee) is ensured. Tests with sensor network protocols similar to *Wireless*HART show that the communication works very well also in a heavily-loaded WLAN environment [6].

3 shows the behavior of such a network during testing, reliability being almost 100 percent all the time.

3 Result of a test measurement of a *Wireless*HART system



WSN for efficient production

WSN is a significant prerequisite for the achievement of cost-effective on-line condition monitoring. The market response with industrial standards and products being launched from a large range of suppliers underlines the growing need for this communication platform. Major oil companies are planning to run pilots with the new *Wireless*HART technology in 2008.

A WSN enabled on-line condition monitoring system contributes to safe and reliable operations by providing early warnings of potentially hazardous situations while also increasing understanding of long term equipment performance and wear. Cost savings result through the reduction or elimination of down time of critical equipment, introducing more effective maintenance concepts and predictable and clear maintenance work processes.

WSN is another example for an enabling technology boosting the business performance of an entire industry that needs to use their assets "to the last drop."

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[3] **Aakvaag, N., Frey, J.** Wireless sensor networks: New-breed networking solutions for industrial automation". *ABB Review* 2/2006.
[4] HART Communication Foundation, http://www.hartcomm.org (January 2008).
[5] ISA-100, http://www.isa.org
[6] **Doyle, P., Vatland, S., Petersen, S., Aasland, C. S., Andersen, T. M., Sjong, D.** Requirements, Drivers and Analysis of Wireless Sensor Network Solutions for the Oil & Gas Industry. Proceedings of ETFA 2007.

Footnote
3) AES: Advanced Encryption Standard

"Lady of Victories"

This self-contained power generation barge is right at home in the Caspian sea

Francesco Gentile

It is 95 meters long and contains over 190 km of electrical and instrumentation cables. It has a total electricity output of 120 MW, is environmentally friendly and since April 2007, the Caspian Sea has been its home. Affectionately known as "Lady of Victories," it is a self-contained power generation barge designed to serve the Kashagan offshore oil field in the Caspian Sea. This Power Generation barge is the result of over two years of fruitful collaboration between ABB and Rolls-Royce Power.

The Kashagan Field is not only the largest oil field discovered in the North Caspian Sea PSA contract area, but globally, it is the largest that has been discovered in the last 30 years. It is located approximately 80 km from Atyrau in Kazakhstan, and covers a surface area of about 3,400 km². It contains an estimated 38 billion barrels of oil, of which 13 billion are potentially recoverable in case of gas re-injection.

Given its size and other factors, the development of the Kashagan field represents one of the greatest challenges in the petroleum industry. These factors include: a deep, high-pressure reservoir; a high sulfur content – of the order 16 to 20 percent – combined with the hydrogen sulfide (H_2S) concentration in the oil to be extracted; shallow waters of between three and four meters that freeze between November and March; the sea-level is also known to fluctuate during the rest of the year; wide temperature variations of the order – 30 °C to + 40 °C are not uncommon; and finally an extremely sensitive environment with a variety of internationally protected species of fauna and flora.

It was decided that the Kashagan field should be developed in three subsequent phases, and this would require the careful co-ordination of simultaneous operations, including development and production, construction of new plants, and the upgrading and expansion of already existing ones. During the three phases, production will increase from an initial level of 75,000 bpd (barrels per day) to a peak of 1.2 million bpd in the second half of the next decade. The proposed development will include both offshore and onshore processing facilities as well as the interconnecting of trunk lines.

ABB's involvement began in the first development phases of the Kashagan field when it was awarded a contract in September 2004 by the sole oilfield operators, Agip KCO B.V., to design and construct a self-contained barge. In fact, ABB's Power Generation Barge 8, completed in collaboration with Rolls-Royce, was to become the first process module to be delivered to the Kashagan Field.

Factbox 1 The Power Generation Module 8 – a technical overview

Main equipment
- Four Rolls-Royce RB 211 6762 30 MW gas turbine generators. Each turbine generator is equipped with a DLE (Dry Low Emission) System. That is, each gas turbine comes with an inlet air filter house, exhaust stack and oil cooler
- Four fuel gas conditioning packages complete with four 60 kW heating streams
- Three 2 MVA emergency diesel generators

Main electrical equipment
- High-voltage switchgear SF_6 Type – 35 kV 40.5 kV insulated voltage
- Medium-voltage switchboard Air Type – 6.6 kV 7.2 kV insulated voltage
- Four 10/35 kV 35 MVA step-up transformers
- Two 35/6.6 kV 25 MVA step-down transformers
- Low-voltage MCC rated to 400 V
- UPS 230 Vca, double redundant, rated up to 40 kW
- DC Battery charger 110 Vcc 20 KW – double redundant
- Batteries – double redundant

I&C
- Load Management System/Distributed Management System LMS/DMS suitable for up to 3,100 inputs and outputs
- A fire and gas detection system

Topside buildings
- Steel structure buildings with a total weight of 300 tons
- Two blast-proof and fire-resistant gas turbine generator buildings (each covering 450 m²) – A60 rated
- An A60 rated fire-resistant electrical building over two floors covering a total of 290 m²
- Pipe racks
- Vent tower

Miscellaneous
- HVAC system:
  Heating: Two 250 kW heating for gas turbine building plus 110 kW heating for main generation building
  Cooling: 180 kW cooling for main generation building
- Fire fighting systems

The Power Generation Module 8

The power generation barge is designed to provide and manage electrical power to the Block D offshore complex in the Kashagan field. The contract included engineering, procurement, fabrication, commissioning and start-up of the Power Generation Module No. 8.

> ABB's power generation barge is designed to provide and manage electrical power to the Block D offshore complex in the Caspian sea's Kashagan field.

The barge weighs about 1,000 tons, is 95 meters long, 16 meters wide and 5.5 meters high, and the hull is made of low temperature carbon steel plates to accommodate the extreme weather conditions of the Caspian sea, as well as to comply with required marine standards[1]. These two factors also dictate the type of materials that should be used for other structural components to ensure that the barge equipment is properly preserved during navigation. For example, heat tracing and insulation has been extensively applied to all piping circuits. The barge is equipped with four 30 MW Turbo-generators and auxiliary systems, gas conditioning skids, a Load Management System/Distributed Management System (LMS/DMS), step-up and step-down transformers, high-, medium- and low-voltage electrical distribution switchgears, and various topside structures. Passive Fire Protection (PFP) requirements for these structures have been met by utilizing special prefabricated panels (certified to "A60" class standard) which guarantee adequate resistance to fire.

A technical summary of ABB's power generation barge is given in Factbox 1.

Footnotes

[1] A certificate from the Naval Authority is required as proof of compliance.

The power generation barge hull was fabricated in sections. The topside structures were prefabricated in a workshop before being transferred to the dry dock.

Sitting in the Malta fabrication yard, the 1,000 ton, 95 meter long, 16 meter wide and 5.5 meter high barge starts to take shape.

Construction overview

ABB PS&S (Process Solutions and Services) Factbox 2, situated in Milan, was responsible for the engineering, procurement, fabrication and commissioning of the complete Power Generation Module, while Rolls-Royce supplied the four fully assembled and factory tested Turbo-generators.

Over 190 km of electrical and instrumentation cables (and relevant cable ways) lie in special segregated areas throughout the barge.

Structural analysis was used to dimension the key components of the hull and topside structures. This analysis also took into consideration the possible dynamic loads during navigation. Pipe and cable routing was determined using 3D modeling, which also helped to supply the construction details for the pipe spools and supports to be fabricated. In all, a total of 100,000 engineering man-hours was required to develop all the engineering details. An experienced and fully equipped company, Malta Shipyards Ltd (MSL), was subcontracted to work on the barge construction.

The barge hull was fabricated in sections, starting with standard steel plates that were then assembled in a dedicated dry dock. The topside structures were prefabricated in a workshop before being transferred to the dry dock for final installation. The entire fabrication process was subject to continuous reviews by DNV (Det Norske Veritas)[2], which then issued a formal "Statement of Compliance" to certify that the quality of the completed work was in accordance with the required international standards.

Over 190 km of electrical and instrumentation cables (and relevant cable ways) lie in special segregated areas throughout the barge, while fire and gas detection devices are positioned all over to allow for constant monitoring. Marshalling panels have been designed to interface with the main plant DCS (Distribution and Control System) and these activate appropriate action when fire or gas has been detected.

Factbox 2 ABB Process Solutions & Services (ABB PS&S)

ABB Process Solutions & Services (ABB PS&S), is an Italian-based company belonging to the ABB Group. It delivers turnkey solutions for the Oil & Gas industry, power plants and electrical and automation systems throughout the world. With an annual turnover of almost $500 million, the company operates through a dedicated Center of Excellence which is situated in Sesto San Giovanni (Milan). The company delivers integrated services including engineering, procurement, construction, commissioning and start-up, as well as a global maintenance service.

Footnotes

[2] Det Norske Veritas (DNV) is an independent foundation whose "core competence is to identify, assess, and advise on how to manage risk. Whether we classify a ship, certify an automotive company's management system, or advise on how to best maintain an aging oil platform, our focus is to safely and responsibly improve business performance." (Extract taken from http://www.dnv.com, November 2007).

The power generation barge contains over 190 km of electrical and instrumentation cables. It has a total electricity output of 120 MW.

Officially named "Lady of Victories," the barge was handed over to Agip KCO by ABB PS&S and Rolls-Royce in April 2007. "Lady of Victories" was finally launched on the 22nd of April.

Once the barge was mechanically complete, marine tests were successfully carried out in December 2006 to check and certify the barge's navigation stability. These tests were witnessed and formally accepted by international Agencies, such as DNV and Noble Denton[3].

Safety, especially at the fabrication yard in Malta, was a priority throughout the entire project. At the beginning of the project, an ambitious goal of zero accidents was set. When an initial target of 500,000 man-hours without any Lost Time Incident (LTI) was reached at the Malta Yard, a ceremony was hosted by representatives of the Maltese Government to celebrate this achievement. In all, out of total of 900,000 man-hours spent at Malta fabrication yard, an impressive 700,000 were without LTI. Safety integration aspects were dealt with at dedicated HAZOP, SIL, and SAFOP workshops and reviews. These workshops were held throughout the course of the project, and were attended by those directly involved in the project, as well as third party consultants.

The complete design was judged by ATEX (The International standards for Hazardous Areas) and SOLAS (Safety Of Life At Sea – International standards that define safety for marine vessels) – to be in accordance with the required benchmarks that ensure PFP. Additionally, the barge fully complies with the required marine standards.

The end result is a power generation plant that meets the highest safety standards, and which is fully compliant with the strictest environmental protection policies.

Critical issues

Certain challenges were faced during the course of the project with respect to the efficient and effective integration of all the various systems on a single unit, while remaining fully compliant with the required industrial and safety standards.

This floating power generation plant meets the highest safety standards and is fully compliant with the strictest environmental protection policies.

The engineering team had to overcome dimensional constraints imposed on the barge because of specific standardization requirements of the Kashagan field. These constraints influenced where and how the equipment and systems on the barge were placed and configured. Three-dimensional modeling was key in handling this issue, as it was used to verify interfaces between different areas, as well as the overlapping of various systems. In addition, it was used to define the most effective layout and routing for piping systems, and power and instrumentation cables. Besides its use in the engineering process, 3D modeling was consistently implemented during the production stage.

Another challenge was the constraints imposed by transit regulations through the various canals leading to the Kashagan field. Even though the barge was fully assembled and tested prior to delivery, these constraints meant that specific components had to be temporarily dismantled after final testing in the construction yard.

A recipe for success

The barge was mechanically completed and pre-commissioned in March 2007 at the Malta yard. In April 2007, it was officially named "Lady of Victories" and was handed over to Agip KCO by ABB PS&S and Rolls-Royce. "Lady of Victories" was finally launched on the 22nd of April.

This remarkable achievement in terms of technology and workmanship would not have been possible without the effective teamwork within the project organization, and the proactive involvement of qualified and reliable sub-suppliers. Seamless integration between the engineering, procurement and construction phases was possible because of the co-operation, knowledge and enthusiasm of each member of the project team. This combination also contributed to the timely and efficient manner in which the barge was completed, and is most definitely, a recipe for success.

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Footnotes

[3] http://www.nobledenton.com/ (November 2007)

Strictly no admittance

Keeping an eye on IT security in the plant

Markus Brändle, Thomas E. Koch, Martin Naedele, Rolf Vahldieck

Electronic attacks on the automation systems of industrial and utility plants are rare. Nevertheless, when they do occur, the consequences can be severe.

Strategies used to protect office networks (for example) are not always directly applicable to the specific needs of industrial and utility plants. Whereas traffic on an office network is largely arbitrary from a monitoring point of view, and intrusion detection is often restricted to scanning data packets for specific attributes, network traffic in a plant is normally easy to correlate to the system's activity. Significant deviations from expected patterns can be an indicator of intrusions. ABB's System 800xA Security Workplace uses this to add security functionality to System 800xA control systems. Because the approach builds on proven System 800xA concepts, operators do not require special IT-security training to be able to make good use of this tool.

In view of the continuous evolution in the capabilities of computers, and also the multiplicity of means of access (network connections, modems, memory sticks, CDs, laptops, etc), it is no surprise that new vulnerabilities are continually being discovered and exploited. No security mechanism can guarantee absolute invulnerability against attacks and intrusions. A polyvalent security architecture therefore relies not only on preventive mechanisms such as firewalls and antivirus tools, but also includes technology and process elements to detect ongoing attacks and intrusions and is able to react to them.

One option for such detection capability is a dedicated team of humans that monitors and analyzes intrusions. Operating such a team around the clock implies a significant and continuous financial investment, which may be hard to justify. Moreover, attracting and retaining qualified team members can prove difficult in an environment that only very rarely encounters an actual attack.

A more cost-efficient alternative for a plant would be to subscribe to the services of a managed security service provider, using central monitoring facilities with highly qualified staff to continuously and concurrently monitor the networks of multiple clients. While significantly less costly than the in-house equivalent, the external service provider approach may still be too costly for low risk plants. Furthermore, there are other concerns that may make this approach unsuitable: These can be related to security, (external access would have to be provided) or to safety (can the external service provider be trusted to properly appreciate the peculiarities of industrial plants and the related hazards?).

For these situations, ABB offers a third alternative – the integration of IT security monitoring in the overall process control structure.

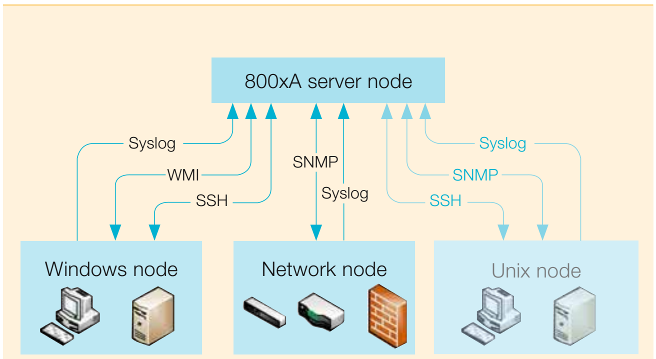
Process operators, thanks to their training and everyday work experience in monitoring hundreds of process indicators, are very good at detecting anomalies in values and their correlations.

Security monitoring and process control
Many companies have technical attack detection capabilities, such as network-based intrusion detection systems, host-based intrusion detection systems, or scanners analyzing log messages from firewalls and hosts. However, many of these companies don't make effective use of these technical capabilities because they lack the staff resources to monitor the output of such tools around the clock.

Whereas IT security for automation systems has to overcome a number of specific challenges, some of them differing from those faced in IT security in offices [1], it also has certain advantages: One of these is that, very often, a process operator is available to monitor system behavior at all times. The availability of the process operator suggests that ideally he should also act as a kind of "first responder" with regard to IT security.

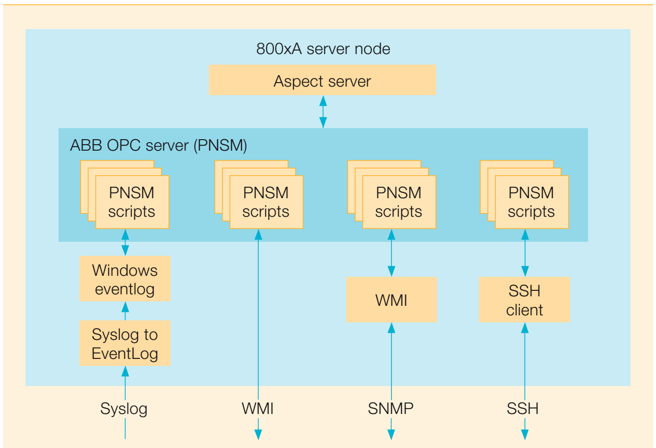
One objection to this approach may be that such a first responder role would require IT and IT-security knowledge, which is often not found among process operation staff. This lack of expertise is being addressed through increased automation of the analysis and detection function using complex rule-bases [2]. The removal of the human with his lack of expertise from the loop permits the derivation of fast and deterministic decisions providing clear responses in clear situations. Many real-life situations are, however, ambiguous: The environment is too dynamic for a fixed attack detection rule-base, and an approach based on dynamic updating of the rule-base would bring back the requirement for continuously available experts. ABB's approach, in contrast, is that process operators, thanks to their training and everyday work experience in monitoring hundreds of process indicators, are very good at detecting anomalies in values and their correlations. These people can use common sense to decide whether there is an uncritical explanation for anomalies – both in control parameters and in security-related areas.

1 Data flow for the System 800xA Security Workplace. Network traffic data is collected from various nodes and analyzed for anomalous behavior.



A more detailed view of the server node is shown in 2.

2 Overview of the architecture of the 800xA Server with Security Workplace

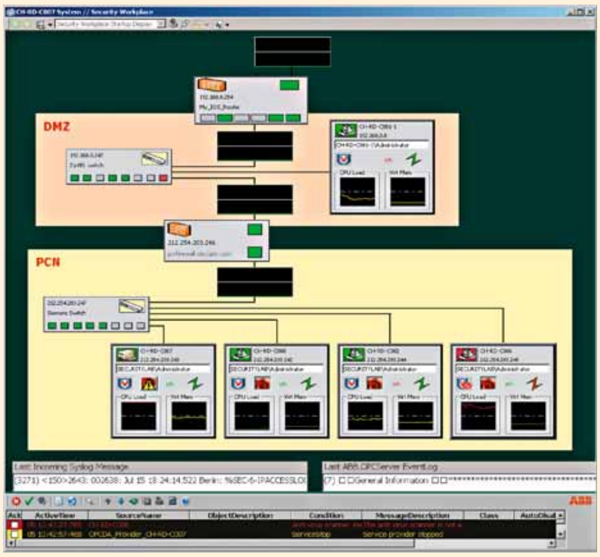


For example: A visualization of the hosts in the automation network displays the number of logged-in users. In the process operator's experience over past weeks, this number is constant. It is not necessary for him to know that the actual value results from logged-in human users (on some hosts) and service accounts for certain applications. Suddenly, he observes that on one host the user count is one higher than normal. Typically, this would be a highly critical sign of host compromise, indicating that an attacker has broken into a user account. In this specific case, however, the processor operator can easily correlate the initial appearance of the additional user on his monitoring system with the fact that a technician has recently entered the control room to effect engineering work. This type of plausibility check is essentially impossible to codify in a fully automated system and the corresponding false alarms are among the main reasons of the poor reputation automated intrusion detection systems have [3].

ABB's vision is to provide the process operator with the tools and methods to deal with plant IT security problems similar to process deviations [4]. The realization of this vision depends on the following prerequisites:

- IT security related information has to be presented to the process operator as part of his normal process-related work environment.
- IT security related information has to be presented to the process operator using the same presentation paradigms he is used to from process monitoring. This includes process graphics, colors, symbols, figures, and trend charts, and excludes messages containing cryptic "hacker terminology".
- The process operator should not need any specific IT or IT-security knowledge in order to detect an attack and react to it in a meaningful way. Possible reactions could include isolating the automation system from external connections, activating predefined network islands inside the automation system, starting a vulnerability check, collecting additional data according to predefined procedures, or calling for expert help.

3 800xA Security Workplace showing the overview of the IT network



Starting from these requirements, ABB has developed a security and system health monitoring and visualization solution for process control systems based on the System 800xA framework – System 800xA Security Workplace.

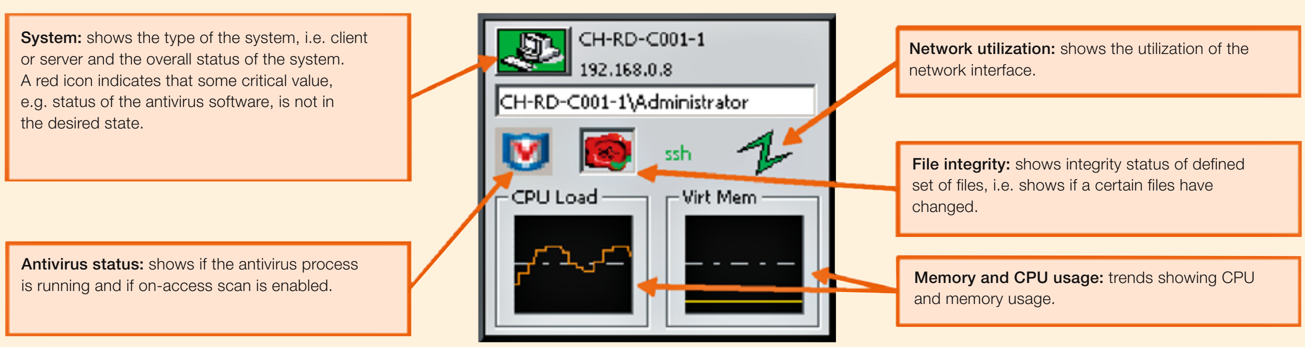
System 800xA Security Workplace

System architecture

System 800xA Security workplace consists of several faceplates and scripts that are loaded into the System 800xA at runtime. The security workplace thus uses and builds upon the 800xA base libraries and framework, illustrating how the high flexibility and straightforward integration capabilities of the 800xA architecture can be extended to such specific purposes as security monitoring.

The 800xA Security Workplace incorporates data from different sources and accessed by different technologies. 1 shows a high level overview of the systems involved and the data flows between them. The current prototype collects data from Windows nodes using Syslog messages, Windows Management Instrumentation (WMI). Data from network nodes (eg, firewalls, switches, or routers) is accessed using Simple Network Management Protocol (SNMP) and Syslog messaging. The current product extension does not include Unix nodes. However, accessing data from Unix nodes is simple using SNMP, SSH, or Syslog messaging.

4 The icon (from 3) showing the status of a computer system in the network



The architecture of the 800xA server node needed to access the data from the different sources is shown in 2. The data is accessed using a System 800xA PC, Network and Software Monitoring (PNSM) scripts and provide the interfaces to connect to the various data sources[1)].

PNSM (PC, Network, Software Monitoring), which is used as the backbone of the security workplace, is a set of 800xA features for monitoring the hosts and network elements in an automation network. PNSM provides a pre-configured library of IT Assets representing devices and system processes widely used within industrial businesses today. Through PNSM, Security Workplace incorporates data from the complete IT system: data from network devices such as firewalls and switches, from network segments and from computer systems attached to the network. The data collected consists of general IT data, such as CPU load, and security specific data, such as information on antivirus installation. Some of these more security related IT assets and information sources were added for Security Workplace.

Overall, the easy integration of information sources and the increasing autonomous behavior of components will lead to the implementation of fully automated and secured plant management. [5].

Operator perspective

Security Workplace is tailored to be used by a "normal" 800xA operator, ie, a person who does not necessarily have an IT-security background and in-depth knowledge of IT networks and systems. The data displayed should therefore not require skilled interpretation – Security Workplace must be capable of highlighting signs of possible attacks. It is not the intention that the operator should be able to identify the type of attack precisely or to react to possible attacks from within the framework of Security Workplace.

The look and feel of Security Workplace resembles a standard 800xA workplace. It contains standard elements such as faceplates, trend displays or alarm lists. Having this seamless integration into the well known working environment fosters acceptance by the operators and does not introduce the additional complexity of a new user interface that a dedicated security monitoring software from an external supplier would introduce.

3 shows the Security Workplace for a demonstration system. It consists of a process control network (PCN), a demilitarized zone (DMZ) and an external insecure network (eg, the Internet or business network). These zones are separated by firewalls and the PCN and DMZ have managed switches to connect the different nodes. The DMZ holds a proxy server that allows the PCN to be connected to from the outside. The PCN holds four different windows systems, an 800xA Aspect server, and 800xA Aspect Optimization server, a Windows Domain server and an 800xA Operator Workplace.

The depiction of the IT system within the Security Workplace resembles the actual physical setup. This will make it easier for the operator to understand what he is looking at. In case of larger systems, which cannot fit onto a single screen, the network can, as is common for complex process pictures, be displayed at different levels of detail on different displays.

For Microsoft Windows-based systems, the workplace overview of the 800xA Security Workplace depicts a summary of the health of the system. 4 shows such a system icon explaining the most important information depicted in the icon.

The overview of the 800xA Security Workplace also contains icons for all network devices. It shows basic information for the devices, ie, type of the network device, IP address, name, and status of the ports. 5 shows icons for a firewall (left) and a router with firewall capabilities (right). The firewall has two ports that are both connected, the router has one port connected to the outside network and six ports connected to the inside network. The icon shows that out of the six ports facing inside, three are connected. The colors of the ports indicate their status, green for correctly connected ports, grey for correctly unconnected ports and red for misconfigured ports, ie, ports that are connected but should not be connected or vice versa.

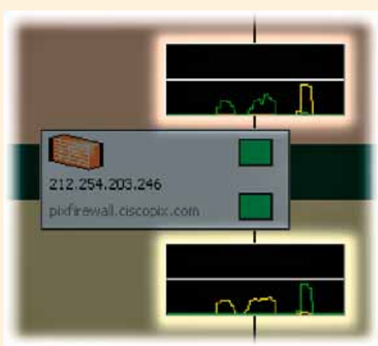
The security workplace also shows information on the network usage on various links. Small trend displays show eg, the amount of data received and sent by a network device or the number of packets received that were discarded 6.

All icons shown in the overview are linked to faceplates offering more extensive information. For network devices, the faceplates show the network usage of all interfaces individually and contain detailed trends for each interface showing the number of

Footnote

1) The different methods of accessing the data are described in detail in technical documentation

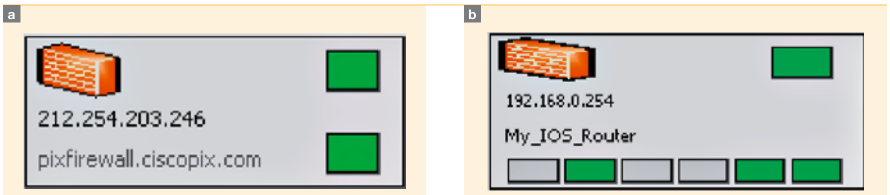
6 Icons showing network loads (green is data received, yellow is data sent)



5 Icons representing firewalls and their statuses, as displayed within the network overview 3

a

b

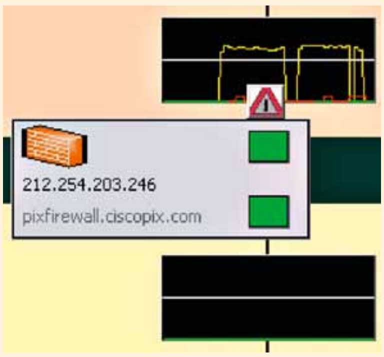


packets received, the number of packets sent, the number of dropped packets, the number of erroneous packets etc. For Microsoft Windows systems the faceplates contain detailed information on the operating system (eg, version, installed service pack), the active sessions, the status of running threads, and trends on CPU usage, memory usage and thread activity.

Example of detection of irregularity

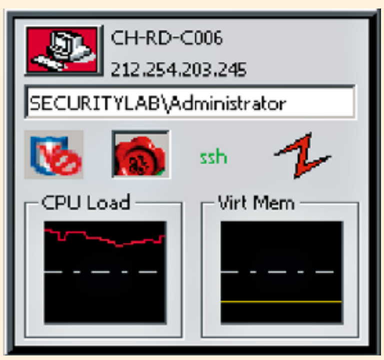
As mentioned above, Security Workplace was designed to detect signs of attacks and to alert the operator. An important part of detecting attacks is first defining a "normal" system state. The workplace allows the definition of thresholds for various values that, when exceeded, will trigger an alarm. In this respect the arrangement is similar to standard process supervision. In contrast to other intrusion detection system (IDS) approaches, however, thresholds are not predefined but it is up to the operator to decide what is normal and what is not.

7 Possible attack on a firewall



8 A switch icon showing an illegal port use (red)

9 A Windows system icon with antivirus turned off



Network loads, for instance, are constantly monitored; a sudden increase of network traffic will result in an alert. Deviations from normal network loads can be a sign for a security incident, eg, network scanning or a malware trying to send data. 7 shows a scenario in which network traffic seen at a firewall is abnormal and one-sided, ie, traffic is only arriving at the firewall and not being re-transmitted. In addition, the network load has crossed the threshold (indicated by the exclamation sign) and some of the packets are erroneous (indicated by the red data plot). The fact that almost no traffic is sent from the firewall on either interface suggests that someone is either scanning the firewall or trying to send data to the PCN that is blocked by the firewall. Both would be a clear sign of an attack. Alternatively, it could be that a technician is uploading a file onto the firewall, eg, a new firmware, causing the abnormal traffic load. However, the high number of erroneous packets makes this unlikely.

Whereas the information shown in 7 gives indications on the type of attack, it is still unclear where the attack is originating from. This information has to be found elsewhere in Security Workplace: 8 shows the network switch residing in the DMZ that is also connected to the outside interface of the firewall. Shortly before the attack the rightmost port in the graphic started to blink in red. This means that a device, eg, a laptop, has been connected to this physical port even though the port should not be connected to anything.

The correlation of the information and the fact that the operator knows that a technician is performing maintenance of the DMZ network allows the operator to assume that the irregularity is caused by the technician's laptop. It can either be that the technician is actually performing a firmware update of the firewall or that the technicians' laptop is infected with eg, a worm that is trying to spread through the firewall.

A different scenario is shown in 9. The monitored Windows system has its antivirus functions turned off and the CPU load is very high. The disabled antivirus software would have triggered an alarm. Similarly to the previous scenario the operator might have additional knowledge to understand the event, eg, someone doing a software update on that machine. However, the antivirus software should typically never be disabled and this scenario would thus have to be classified as a security incident regardless of the circumstances.

The System 800xA Security Workplace and associated integration services are available from ABB ConsultIT Security Consulting Services. Contact Rolf Vahldieck (rolf.vahldieck@ch.abb.com) or the other authors of this article.

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[2] http://www.sandia.gov/news/resources/releases/2006/logiic-project.html (November 2007)

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Further reading

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A secure future

ABB's Remote Monitoring and Operation Services are changing the way process automation systems are controlled

Ragnar Schierholz, Bjarte Birkeland, Martin Naedele

Information technology (IT) is now being used by most companies as a way of effectively controlling and monitoring their process automation systems. While modern information and communication technologies allow access to remote and confidential information simply by clicking a button, the danger that unauthorized personnel can illegally gain access is ever-present. Significant efforts are being made by these companies to protect their automation systems against cyber-attacks and other information security related threats. These efforts are also necessary to comply with industry standards and the increasing number of regulatory requirements that are coming into effect. The downside, however, is that many companies must build-up substantial expertize in the field of IT security, and this can be very costly.

Another way of approaching this is to find a reliable partner who can provide the services which allow them to be compliant without having to invest in new resources. One such company who can do this is ABB. Using its Remote Monitoring and Operations Services, ABB can guarantee the secure operation of a company's process automation system while the customer concentrates on the important business of increasing its profit line.

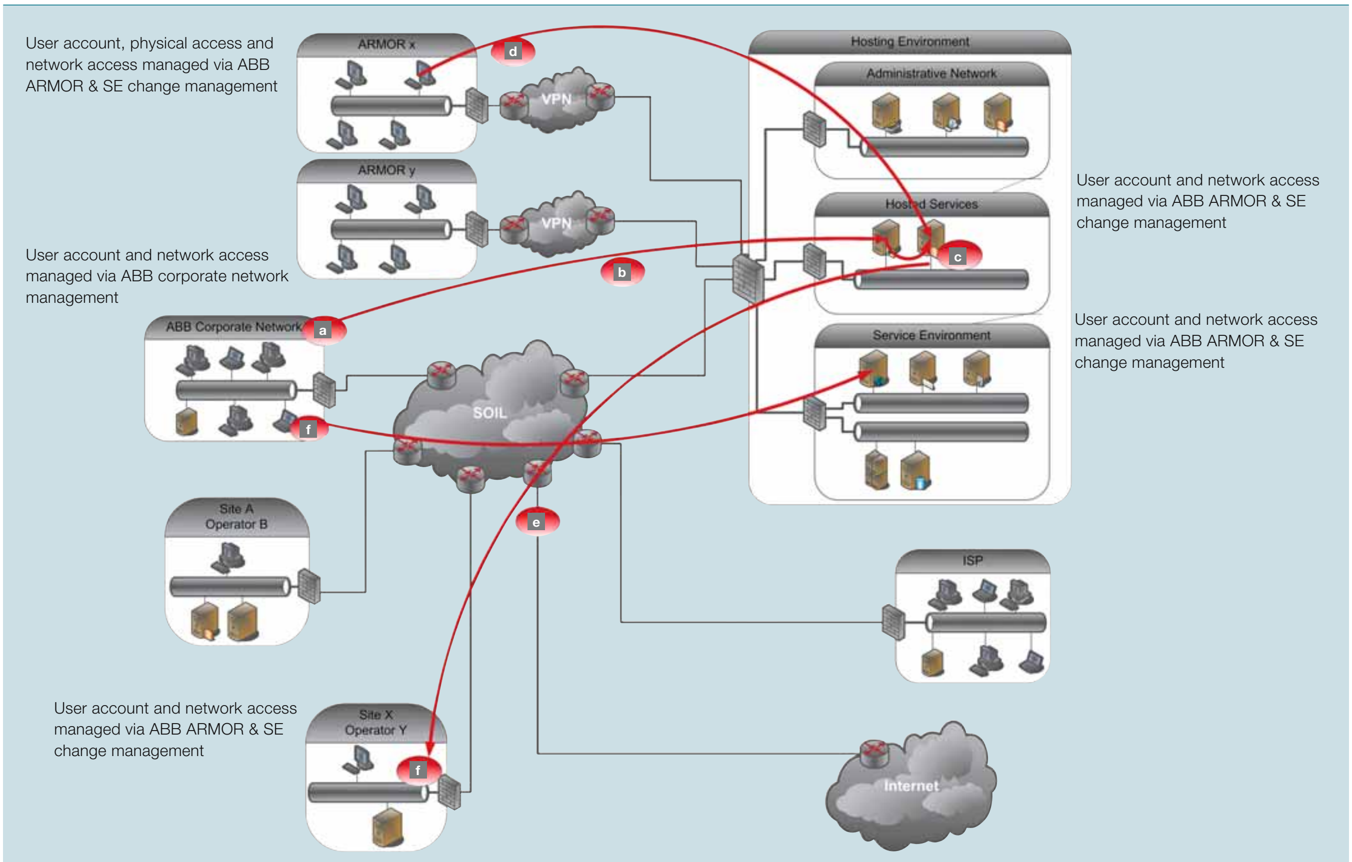
Information technology (IT) is helping many businesses to streamline their processes, and those who have gone down this road have seen an increase in productivity and higher profits. The Norwegian Oil and Gas industry, under the heading of "Integrated Operations (IO)[1]" , is currently on this journey. Integrated Operations, as defined by The Norwegian Oil Industry Association, the OLF, is "the use of information technology to change work processes to reach better decisions, remote-control equipment and processes, and to move functions and personnel onshore." The main idea of IO is therefore to streamline all work processes (ie, planning, production, and maintenance) across organizations (such as oil producers and their suppliers) and locations (on-shore and off-shore). The expected benefits include an increase in the amount of oil recovered, the acceleration of production, and the reduction of operational costs. OLF reckons that implementing IO will require an investment of approximately 25 billion NOK (US $ 4.6 billion), while the potential value of the investment over the next 15 years is estimated at 250 billion NOK (US $ 46 billion).

Modern information and communication technologies are the foundations

Footnote

[1] http://www.olf.no/english/news/?52210 (December 2007)

1 Sample process for remote work: A typical process flow, with the relevant security mechanisms for remote work on customer sites. An example scenario of updating a locally installed application, involving both file transfer and interactive access to the target host is depicted.



a Input:
- Newly discovered vulnerability & patch
- Configuration data

Activities:
- Analyze vulnerability
- Assess criticality
- Test patch & develop action plan
- Identify relevant assets
- Approve action plan in CAB

Connected processes:
- Field alert management
- Configuration management

b Activities:
- Upload patch files to file server

Connected processes:
- Change management – user accounts on file server

c Activities:
- Automatic virus check on file server
- Transfer to user environment on terminal server

d Activities:
- User entry to ARMOR
- User logon to terminal server

Connected processes:
- Change management – access to ARMOR
- Change management – user accounts on ARMOR host and terminal server

e Activities:
- File transfer to target at customer site
- User logon to target at customer site
- Local install of patch on targets according to approved workplan

Connected processes:
- Change management – access to connectivity to customer site
- Change management – user accounts on target host at customer site
- Change management – approved workplan

f Activities:
- Update of configuration data in CMDB according to performed workplan actions

Connected processes:
- Change management – approved workplan
- Change management

upon which IO depends. However, establishing separate connections to remote sites, such as oil rigs in the Norwegian Sea or gas fields at the North Cape, for each operator and each supplier is wholly inefficient. The most economical solution, therefore, uses a shared infrastructure based on current Internet technology. Connectivity based on Internet technology or even to the Internet itself requires a much higher level of information security than previous isolated control system installations. The OLF has addressed this by issuing a set of baseline requirements for information security (ISBR) in oil and gas production. In fact, these requirements are aligned with many international security guideline initiatives.

Remote Monitoring and Operation

ABB is no stranger to the world of IT. Its Remote Diagnostic Service offering has been successfully helping customers increase the return on their assets by optimizing plant operations and reducing maintenance efforts. Now ABB has gone a step further to ensure secure operation within the process automation domain. By adapting its IT Service Management approach to the IT Infrastructure Library (ITIL)[2], ABB has extended its service portfolio to include Remote Monitoring and Operation Services. With this set of services, aspects such as incident management, maintenance of a site inventory database[3], system setup and maintenance, as well as remote condition monitoring for ABB and third-party equipment, secure client and server management, or on-site and remote backup are covered 1. If all these services are contracted out to ABB, an operator not only obtains remote automation system maintenance services that are secure and regulation compliant, but he also benefits from ABB's IT security and management expertize without having to invest in new in-house resources. In other words, the security and well-being of the entire system becomes the responsibility of ABB.

A safe and secure environment

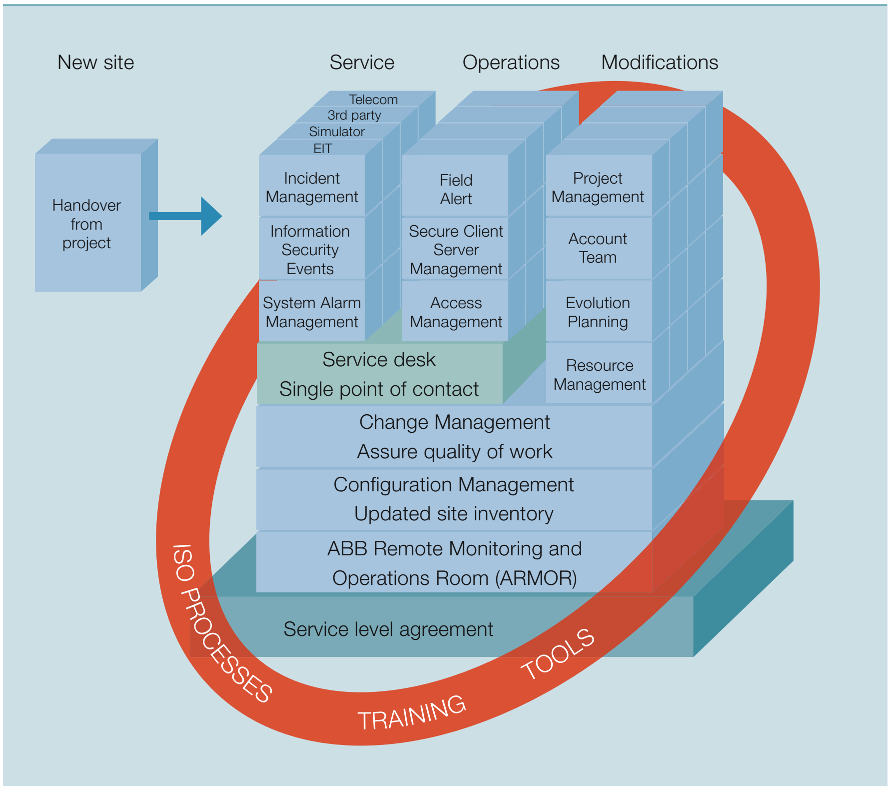
In providing such a service, ABB uses an infrastructure that consists of four high-level components:

- Remote access to on-site automation systems including interactive access via terminal services, as well as file transfer facilities.
- Specially secured on-shore operator rooms, known as ARMOR (ABB Remote Monitoring and Operations Room), in multiple locations. Remote work on "hot" installations can only be performed from within these special rooms.
- A multi-tenant[4] service desk application suite (Service Environment, SE). This suite offers all the functionality required for the management of service requests and other incidents. It also features a Configuration Management Database (CMDB) which forms the basis of the site inventory service and provides data for various other services.
- An office environment in which service desk staff works and where test environments for product configurations are available.

With ABB's Remote Monitoring and Operating Services, an operator obtains remote automation system maintenance services that are secure and regulation compliant.

Connectivity between these components is established via a Secure Oil Information Link (SOIL) and dedicated

2 The main customer support and modification processes within the Service Environment



Footnotes

[2] The IT Infrastructure Library (ITIL) is a comprehensive process framework for IT service management, originally developed by the UK Government's Central Computer and Telecommunications Agency (CCTA). It combines multiple previous approaches into a coherent set of processes. However, the processes are described on a generic level and a more detailed, organization-specific definition has to be developed to implement the ITIL approach. For more information on ITIL see http://www.itil-official-site.com/ or http://www.itil.org/.

[3] Each site, such as an oil rig, has its own inventory, and all site inventories are separately stored in a centrally operated database.

[4] Multi-tenant refers to the ability of a hosting site to hold data and provide functionality to multiple customers at the same time. It behaves as if it were a separate system for each customer. This allows for lower operational costs and higher efficiency and scalability.

virtual private networks (VPN). SOIL is an extranet operated by a consortium of all major players in the Norwegian oil and gas market. It provides network connectivity and basic network services to its members in the North Sea Oil & Gas industry, and its use is being extended to include other players around the world.

The security requirements for any service infrastructure are mainly influenced by two things: The security of the customer's automation system and automation network must not be endangered; and the remote access infrastructure, ARMOR and SE, has to be protected against malicious interference. In both cases, perimeter protection, account management and access control, malware protection, and patch management are therefore required. These solutions must be compliant with standards and regulations for general and process automation system security. Besides technical security controls, operational procedures that ensure continuous security management and secure operations must also be in place.

The application of ABB's infrastructure in a process automation system environment is described in the following paragraphs.

ARMOR and the SE architecture

Remote access to on-site systems is realized through a multi-tiered architecture. The first tier consists of the ARMOR rooms. Access to these rooms is only possible with a PIN-protected magnetic swipe card, which is issued after the employee has undergone special training[5]. The computers in each ARMOR room are located in a locked cabinet. Access is limited to administration staff only and is not allowed during remote work. User accounts on these workstations are managed via ABB's Secure Client and Server Management service. Each ARMOR network is connected to the hosting environment via a dedicated VPN connection, and the perimeter of each network is protected by a firewall. Only network connections between the ARMOR rooms and dedicated servers in the hosting environment are allowed.

The second tier is a server infrastructure in the hosting environment. Included in this environment are: terminal servers, which the users in the ARMOR rooms connect to; file servers that allow file transfers between sites; a web server; an application server; and a database server. Additional servers for administrative purposes, such as domain controllers and backup servers, can also be found in the hosting environment. A set of firewalls protect the hosting environment and only clients in authorized network segments (eg, from ARMOR or registered customer sites) using authorized protocols can connect the servers. Servers with different functionalities are separated by VLANs, and connection is only possible through a firewall. In doing this, different security levels can be applied to the various servers.

For interactive access to customer sites, screen mirroring applications, such as Citrix or Microsoft Terminal Services are used. Inbound connections to the terminal server are allowed only if they originate in the ARMOR rooms. Outgoing connections are only permitted to registered terminal servers at customer sites using the protocol registered for the respective server. Each authorized user has an individual account on the terminal server. Individual user profiles will contain information concerning only the terminal servers at a customer site that the user is authorized to use. The authorization and registration of customer sites is managed via the change management process.

Besides technical security controls, management processes are key elements of common information security standards and regulations.

For file transfers between customer sites, the same authorization is applied. Users cannot place data on the ARMOR workstations. Instead, data required for remote work on customer systems must be transferred to a file server in the hosting environment via SSL-secured sessions. On the file server, the data is scanned for viruses and other malware. If the scan is negative, the data is made available in the user's terminal server session and can be transferred to customer systems.

Customer systems, which constitute the third tier, may be servers, such as OPC servers, or System 800xA nodes or clients, such as System 800xA operator workstations. A typical customer system may consist of sub-tiers. Interactive access to, as well as file transfer to and from on-site systems is performed according to procedures defined by customer security policies. These may mandate technical details, such as file transfer mechanisms via secured FTP or encryption endpoints, with detailed logging under customer control[6].

Besides technical security controls, management processes are key elements of common information security standards and regulations. These typically include incident management, change management, configuration management, field alert management and business continuity management 2. Process definitions and operational guidelines that comply with relevant standards are in place for the ARMOR and SE operations.

Management processes – an overview

Field alert management covers both the customer system and the external environment. Using the Asset Optimizer component of the System 800xA product line, the customer's process automation system is continuously monitored so that failures can be prevented. Data is sent from the system to the service desk application where it is processed and viewed by operations staff. This data includes information about the security status of the process control system, for example the number of failed login attempts, the number of active sessions, or if there has been an excessive number of denied connection attempts on the firewalls. The operator is alerted to any data that meets predefined condi-

Footnotes

[5] Refresher courses must be taken once a year

[6] For accountability purposes

tions (eg, a certain number of failed login attempts) or deviates from normal behavior. When this happens, the data is dealt with using *incident management*. As regards incidents stemming from the external environment[7], a list of products – both ABB and third party – used on any contracted site is maintained. For these products, information, such as update notifications or vulnerability disclosures, is monitored. The disclosure of vulnerabilities, new updates or patches is evaluated by a service team, which then derives some form of implementation plan. Using the CMDB, the service team identifies affected systems and initiates a *change management* process to take any necessary action. Incident management can also be triggered by service requests submitted by customers, and how these are dealt with depends on the nature of the incident. Some cases will be handled by the service desk application, while others will be referred to the change management process.

In the change management process, all change requests and their associated documentation (eg, test reports for updates or patches) are reviewed and approved by a site-specific Change Advisory Board (CAB). Besides incident management, release management may also trigger the change management process.

Effective changes in a system's configuration are handled in a configuration management process. All relevant information for system operation and service, including configuration items such as network nodes, applications or users, is maintained in the CMDB. The *configuration management* process ensures that all configuration items are properly registered and updated, enabling ABB to present an accurate inventory of the entire process automation system at any time.

Customers in other industries, such as power utilities or process plants, will soon be able to reap the benefits of ABB's service environment.

Vision for the (not so distant) future

In recent years, ABB has consistently shown itself to be aware of and concerned about IT security issues in automation systems. The goal of ABB's Remote Monitoring and Operations Service offering is to translate this expertize into a comprehensive set of services that will not only assist ABB customers in operating and securing their automation systems and plant networks, but it will also ensure they are in compliance with standards and regulations, as well as industry best practices. This assistance could extend right up to the remote operation of the entire process automation system by ABB service staff. For this purpose, the company plans to install ARMOR-type facilities around the globe, beginning in regions with strong oil and gas industries, such as the Gulf of Mexico or the Middle East. In doing this, ABB will be able to provide efficient and expert assistance around a clock to a larger number of customers.

ABB's service environment is not limited to the Oil & Gas industry alone. Customers in other industries, such as power utilities or process plants will soon be able to reap the benefits of these services. Using the expertize acquired in the Oil & Gas Industry, ABB Corporate Research is currently working on a reference architecture for secure remote access infrastructure that is suitable for other industries, as well as other business units.

Shell has entered into a full Service Environment contract with ABB. Signing the contract are Shell's Director of Operations, Gunnar Ervik, and Bjarte Pedersen, Director, ABB Oil & Gas

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Footnote

[7] "External environment" in this context refers to external information relevant to a system component that triggers an incident (as opposed to an alert coming from a system component).

125 years running

From the very beginning, ABB has been a pioneer in electrical motors and machines

Sture Eriksson

Rotating electrical machines have played a fundamental role in the development of modern society. They generate practically all electricity and perform most of the mechanical work in industries, public sectors and private households. The electrical motor is, by far, the most versatile type of motor, overshadowing combustion engines, hydraulic and pneumatic motors, as well as different types of turbines. The electrical motor's dominance is mainly due to its simple and clean supply of power, relatively low costs, high efficiency and reliability, good controllability, and adaptability to different applications. These rotating electrical machines cover an unrivaled power range, from microwatts to gigawatts. ABB, along with its predecessors ASEA and BBC, has contributed significantly to electrical machine development, especially for industrial and infrastructure applications.

PERPETUAL PIONEERING

The basic electromagnetic discoveries that were prerequisite to the development of electric motors were made in the 1820s and 1830s, with inventions of some primitive electrical machines being presented by the mid-19th century. The manufacture of useable machines began in the 1870s. Such electrical machines were fundamental for the establishment of both ASEA and BBC.

The Swedish company ASEA was founded in 1883 as a result of the invention of a DC dynamo by a young engineer called Jonas Wenström (1855–1893). These dynamos were intended for the supply of power to lighting installations 1. In 1890, Wenström was also granted a patent for a three-phase system, which consisted of a synchronous generator, a transformer and an asynchronous motor. Wenström is considered one of a few independent inventors of the three-phase motor.

In 1891, Charles E. L. Brown (1863–1924) founded, in partnership with Walter Boveri (1865–1924), the BBC company. Earlier, Brown had been manager for the electrical department in another Swiss company, Oerlikon. There, Brown developed both AC and DC machines, most notably the generator for the world's first three-phase transmission. Charles Brown contributed several other brilliant inventions around the turn of the century, eg, the turbogenerator with cylindrical rotor.

Technical aspects
The function of both generators and motors is based on the interaction between electric currents, magnetic fluxes and mechanical forces. The implementation can be made in several different topologies, but most common has been the traditional radial flux machine with inner rotor and outer stator. A relation for the output of such a machine is given by Equation 1 derived from Maxwell's equations.

Equation 1 $P = k \cdot n \cdot D^2 \cdot L \cdot A_s \cdot B_\delta$

where:
P = power, k = a constant, n = speed, D = air gap diameter, L = active length, A_s = linear current loading, B_δ = airgap flux density

The development of electrical machines has been heavily dependent on other technology fields.

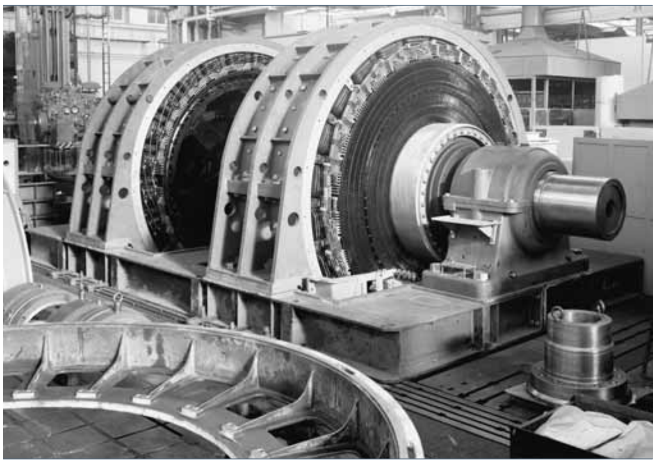
This equation shows that the output is proportional to the speed of rotation, to the physical size of the machine, the airgap diameter and its active length, the linear current loading, and the airgap flux density. Electrical machine designers have always strived to develop smaller and more cost-effective generators and motors. At a given speed, Equation 1 indicates that the machine size can only be reduced by increasing the current loading and/or the flux density. The latter is limited by magnetic saturation of the iron in stator and rotor cores. What remains is the increase of the linear current loading resulting in higher copper losses in the windings. This was the traditional method for developing more and more compact machines by means of materials that could withstand higher temperatures and application of improved cooling methods.

Electrical machines are subject to several types of stresses – electrical, mechanical, thermal and chemical – and often combinations thereof. The insulation must be able to withstand a high electrical field strength, and rotors must be designed with respect to centrifugal forces. Other mechanical stresses include those caused by stationary and transient electro-dynamic forces. In spite of high efficiency, the losses lead to high temperatures in different machine parts. Hazardous atmosphere, humidity and dust also constitute stresses that must be taken into account. It is no surprise then that electrical machine development has become a multi-disciplinary activity, requiring specialists in electrical, mechanical and material sciences, to mention a few.

Development
The 125-year development has focused on customers' need for more reliable and cost-effective machines. Numerous different machine types and variants have been designed to meet the requirements for each individual application. Many industrial drives require wide and accurate

1 Wenström's first dynamo built in 1882

2 Double-armature DC-reversing mill motor; BBC tandem drive from 1956



speed control. Others are located in atmospheres that are so hazardous that the motors must be explosion-proof. Original equipment manufacturer (OEM) customers, such as compressor or pump manufacturers, often specify special motor designs not entirely in accordance with the motor manufacturer's standard. The list of examples is extensive.

The development of electrical machines has been heavily dependent on other technology fields. Material technology has been of utmost importance since the very beginning. Another more recent and equally important area is power and control electronics. Computer-based engineering tools and simulation programs, for example, also had a significant impact.

DC drives with static converters first came into use during the 1930s when grid-controlled mercury arc rectifiers became available.

DC motors

DC generators and motors formed the basis for the early development of ABB and were also major products for BBC's initial business. A great advantage of this motor type was the ease with which its speed could be controlled, which explains why it has survived until even now. The motor speed is proportional to the voltage and to the inverse of the magnetic flux as indicated by Equation 2.

Equation 2 $n = k \cdot E/\Phi$

where:
n = speed, k = a constant,
E = electromotoric force (induced voltage), Φ = magnetic flux

DC motors are often voltage controlled up to a certain base speed and flux controlled above this speed, resulting in a constant torque region at lower speeds and a constant power region at higher speeds.

The first DC motors were manually controlled by means of resistors – a very inefficient method. A big improvement was the introduction of the Ward Leonard motor control system in which the DC motor was supplied with a variable voltage from a rotary converter consisting of an AC motor and a DC generator. The system not only provided good speed control but it even facilitated regenerative braking. The drawback was, of course, that it required three machines and was therefore expensive and voluminous. The Leonard system was used both by ASEA and BBC from the early to mid-20th century for applications such as paper machines, rolling mills, mine hoists, cranes and machine tools. The growth of motor size was fast – eg, a DC motor for a maximum output of 7,000 kW was delivered in 1915 to a Swedish reversible rolling mill.

DC drives with static converters first came into use during the 1930s when grid-controlled mercury arc rectifiers became available. This improved the system efficiency by 4 to 5 percent compared with the Leonard system, but the rectifiers were expensive and were only used for the supply of relatively large motors. However, these two drive systems were state-of-the-art for demanding applications such as rolling mills and paper machines, until silicon-type semi-conductor converters were introduced around 1960 – first diode rectifiers and soon thereafter thyristor rectifiers. The first thyristors were not powerful enough for very large drive systems – only up to 300 kW – but the development was fast and motors for 12,000 kW were being built by the end of the 60s. DC motors also have been widely used for vehicle propulsion; eg, in trams and trolley buses, fork lifts and electric cars, as well as locomotives and other rail vehicles. These traction motors were usually series-excited until separate excitation became the most common system for converter-fed motors.

All DC machines were outer-pole machines with the armature winding placed in the rotor and connected to the commutator. They were often open ventilated or closed with separate cooling from an external fan. The stator ring and the poles were, for a long period, made from solid iron. But the need for fast control and the introduction of thyristor rectifiers, which caused a lot of harmonics, led to the use of laminated steel in the stator. Commutation has always been a critical and limiting factor for DC machines, even after the situation improved with the use of commutation poles and compensation windings in the early 1900s. Reversible drives, eg, rolling mills, required such a fast change of rotation direction that big efforts were made to develop motors with low inertia. In many cases, it was even necessary to split the power between two mechanically series-coupled motors, known as tandem drives 2.

A remarkable DC motor was supplied by ASEA to the USSR in the mid-1970s for driving a large medical centrifuge to train cosmonauts. This motor, which could accelerate the centrifuge with a torque of 1,100 tm, had a vertical shaft and is probably the largest DC motor ever built. Until then, the largest rolling mill motors had maximum torques of approximately 400 tm.

A remarkable DC motor was supplied by ASEA to the USSR in the mid-1970s for driving a large medical centrifuge to train cosmonauts.

The end of the DC motor era has been proclaimed again and again over several decades and nevertheless the technology has managed to survive, although with a much-reduced market share. The DC motor is easy to accurately control, and it is still preferred by many customers for applications such as cranes and mine hoists, mixers and extruders, ski lifts and test rigs, to mention a few. Today, ABB offers DC motors with an output range of 1 to 2,000 kW. ABB's latest series of such motors, covering the output range of 25 to 1,400 kW, was introduced only a few years ago.

Asynchronous motors

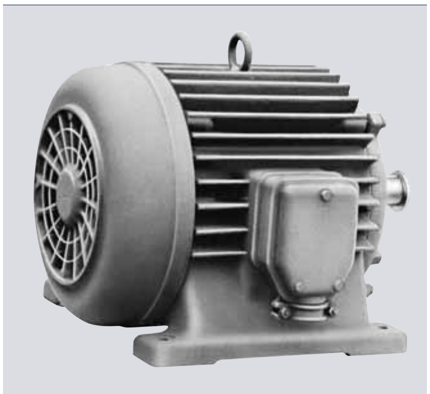
Asynchronous motors, often called induction motors, can be divided into different groups according to the type of cooling, mounting, voltage, etc. Two common basic categories are:

- Motors with short-circuit rotors provided with so-called squirrel-cage windings
- Motors with wound rotors with the windings connected to slip rings

Both of these types were built by ASEA, BBC and several other manufacturers already before the end of the 19th century. The induction motors were less expensive than other motors and were very robust, and soon became the most common industrial workhorses. Manufacturers developed their own standard series of smaller motors, which were documented in catalogs around the turn of the 20th century.

Most of the old induction motors were open ventilated, and had cast iron stator frames and sleeve bearings. ASEA introduced ball bearings for small motors in 1910, and such bearings became more widely used in the 1920s and 30s. The need for safer motors in industries with dusty or even hazardous atmospheres led to the development of closed motors. These motors had to be derated with respect to the open motors, but the situation was improved by the introduction, in 1930, of forced surface cooling, ie, an external shaft-mounted fan that blew air along the outside of the stator, which was provided with axial cooling fins 3. The slot insulation was first made from particle board (presspan) combined with impregnated cotton fabric, but the latter was replaced by less moisture-sensitive materials in the mid-1920s.

3 Three-phase squirrel-cage motor with ball bearings, completely enclosed with external fan cooling (1934)

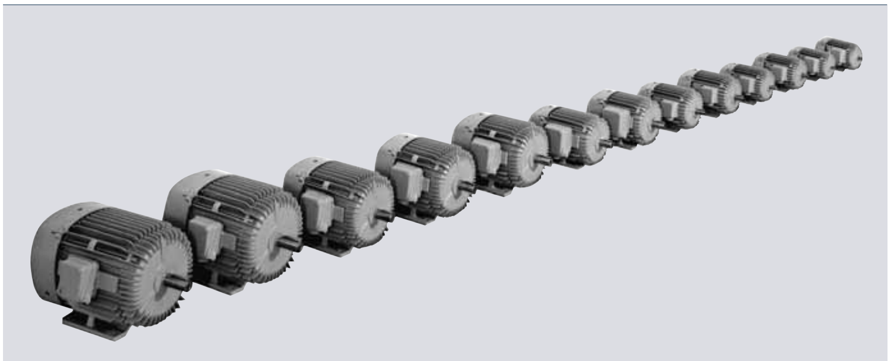


> Smaller induction motors became more and more of a commodity, and customers wanted the ability to switch between motors from different suppliers.

Insulation of the individual copper strands was improved at the same time. The squirrel-cage windings in the rotors were made of copper bars placed in circular slots and soldered to short-circuit rings. Rectangular copper bars were introduced in these windings during the 1920s, significantly improving the starting properties. Brazing or welding replaced soldering for connection of the bars to the short-circuit rings.

Slip-ring motors were very common as long as the power grids were too weak to allow for direct-on-line starting. An outer resistor connected to the rotor winding via the slip rings limited the current and increased the torque. The resistance was successively reduced until the slip rings could be short-circuited. In the early 1920s, BBC developed a centrifugal starter consisting of a rotating resistor and a switch that short-circuited the resistor when the rotor had reached a certain speed. This invention improved the starting properties compared with squirrel-cage motors when it facilitated the use of wound rotors and start resistors while eliminating slip rings and external equipment. These motors were quite common for several decades.

4 Small motors with dimensions to IEC recommendations from 0.12 kW to 7.5 kW (1961)



Low-voltage motors and larger high-voltage machines are very different in several respects. The first category is standardized and much of the development has been process oriented. The production volumes have been large, and motor factories have been established in many countries over the years, both by ASEA and BBC. In 1935, an important step in product and process development was introduced by BBC with the squirrel-cage windings of cast aluminum for motors up to 3 kW. ASEA launched its first series of small motors with stator housing and rotor winding from cast aluminum in 1945. Modern synthetic insulation systems based on polyurethane and polyester replaced the old systems a few years later.

Smaller induction motors became more and more of a commodity, and customers wanted the ability to switch between motors from different suppliers. This created pressure for a common standard, which led to the standardization of dimensions, such as shaft height and footprints, as well as standardized ratings (output, voltage and speed). These kinds of standards were introduced by the International Electrotechnical Commission (IEC) in 1959 and in the United States by the National Electrical Manufacturers Association (NEMA) somewhat earlier 4. They have, of course, been subject to a number of revisions throughout the years, but are basically unchanged. Cost reduction has always been a major development goal but much of the recent induction motor development has also focused on improved efficiency and lower noise.

Methods for varying the speed of slip-ring motors through slip control had been long used, but they had significant limitations. The most successful type was the "Scharge" motor, inserted in 1910. Typical applications have been textile machinery, printing presses and others 5. When thyristors became available in the 1960s, allowing forced commutation of inverters, it was suddenly possible to develop variable-speed induction motor drives based on frequency control. In 1964, two BBC engineers presented a method for so-called pulse-width modulation (PWM), which later became the standard for this type of control. It took some years until this technology was ready for commercial introduction – BBC started delivering such drive systems during the 1970s, while ASEA preferred DC motors. However, the Finnish company Oy Strömberg Ab, acquired by ASEA a year before ABB was established, also belonged to the frequency control pioneers: Its knowledge and resources permitted the Finnish unit to establish itself as ABB's center for such drive systems. The inverters created current and voltage harmonics – especially in the first generations – which caused problems for the motors. The current harmonics induced eddy currents, and hence extra losses and overheating, and motors had to be down-rated. Other issues were insulation failures due to steep voltage spikes and capacitive bearing currents that could damage the ball bearings. New types of frequency converters and improved motors have practically eliminated these problems.

Synchronous permanent magnet motors have become an alternative to the induction motor for certain applications, especially low-speed, high-torque drives. This has been feasible due to the development of very powerful rare-earth magnets in the 1980s. ABB has launched a series of such motors, primarily for use in the pulp and paper industry. Even if there are alternative motor types, the induction motor will remain dominant due to its superior properties for fixed frequency drives and its competitiveness in terms of variable-speed drives.

> The development of synchronous machines has primarily been focused on large high-voltage machines, such as power plant generators

Synchronous machines

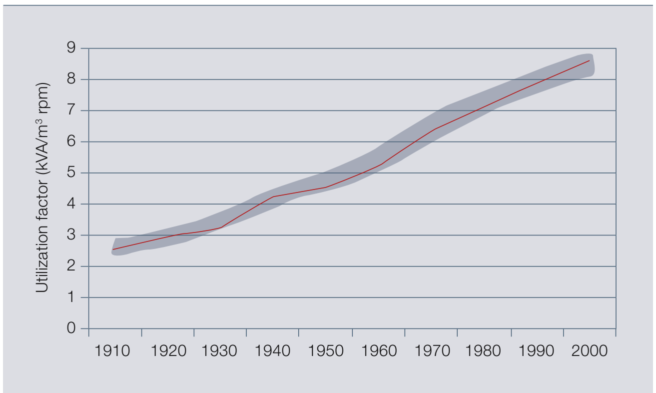
The development of synchronous machines has primarily been focused on large high-voltage machines, such as power plant generators, large motors and synchronous condensers. The generators, covering the range from high-speed turbo-generators to low-speed hydropower generators, were in many respects leading the development. Over the years, ASEA and especially BBC have built many large machines that have been milestones in the international evolution of power plant generators. 30-MVA machines were built in the early 1920s, and 100 MVA was passed in the 30s. Later, both companies would build much larger generators.

The old salient-pole machines had stator frames, rotor hubs and cores, as well as bearing pedestals, all from cast iron. Soon, steel casting replaced cast iron in rotating components, thereby increasing the safety with respect to fractures. Welded designs were introduced in the 1930s. These both increased the mechanical strength and reduced the weight of the structural parts. Stator windings of different types were used: Concentric windings with one coil side per slot dominated for multi-pole machines until the late 30s, when lap windings with two coil sides per slot became more common. For a long while, such windings were used for turbo-generators, offering better possibilities for rational production. The coil sides were, for larger machines, often Roebel bars in which the tiny copper strands were transposed within the coil side. This globally used method was invented and patented in 1912 by BBC engineer Ludwig Roebel (1878–1934). Originally, the companies used shellac-impregnated mica foil for insulating the high-voltage stator windings. Asphalt and mica insulation then came into use around 1930, mainly for machines with higher voltages. A new insulation system based on synthetic resins was developed and introduced by BBC in 1955 under the trade name MICADUR®. ASEA launched corresponding systems during the 1960s: One that used vacuum and pressure impregnation of the mica and glass tape, and one that used semi-cured, pre-impregnated tape.

Cooling is essential for electrical machines: The larger the machines are, the more sophisticated the cooling systems must be. The develop-

5 Three-phase shunt commentator motors with pipe ventilation and built-in spinning regulators (1965)

6 Utilization factor of large air-cooled salient pole synchronous machines



ment has gone from open-ventilated machines to closed machines with forced cooling by either external fans or inner shaft-driven fans, which circulate the air through attached heat exchangers 5. The latter is most common for large synchronous machines. Later, between the 1940s and 1970s, very efficient systems, such as hydrogen-cooling and direct water-cooling systems, were developed for very large machines – namely, turbo generators and synchronous condensers.

The excitation current for the synchronous machines was usually provided to the rotor winding via brushes and slip rings from shaft-driven or separate exciters (DC generators). In the 1960s, the availability of silicon diodes made it possible for ASEA and BBC to build a maintenance-free, brushless excitation system consisting of a three-phase generator with a rotating armature winding and a rotating rectifier that could be directly connected to the rotor winding in the main machine. This required that the diodes withstand high centrifugal forces, in some cases up to 5,000 g. This kind of excitation system has become increasingly common.

Large synchronous machines are used as generators driven by steam and gas turbines, water turbines, diesel engines, and wind turbines. Typical motor applications are compressor drives, large pumps and fans, refiners, rolling mills, mine hoists and ship propulsion. Synchronous machines are more efficient than induction motors; they also enable control of the power factor, but they are more difficult to start. Earlier, ASEA and BBC developed methods for the asynchronous start of synchronous motors. This involved pulling the motors into synchronism by exciting them at near full speed. Such methods are used even nowadays for large salient-pole machines with solid pole plates – a very demanding mode of operation.

The variation in output, speed and other requirements is so wide that standardization of larger machines has been difficult. Many machines were formerly tailor-made, but later development focused on modularization and standardization of components. The machines have become more cost-effective and their specific output has increased, as illustrated in 6. The largest synchronous motors ABB has built thus far are rated at 55 MW. (The company has built turbogenerators rated at up to 1,500 MVA and salient-pole generators rated at 823 MVA.)

In 1998, ABB launched a radically different type of synchronous generator for very high voltages, called Powerformer®, and two years later a corresponding motor, Motorformer™. The stator winding consists of high-voltage cross-linked polyethylene (XLPE) cable, enabling machine voltages in the range of 50 to 200 kV, substantially higher than for conventional machines 7. This allows the machines to be directly connected to a transmission line and step-up (or step-down) transformer, and can eliminate the need for bus bars and some switchgear. The maximum voltage up until this point was 155 kV for a hydropower generator. Earlier machines with unusually high voltages include a 20 kV generator delivered by ASEA in 1906 and a 36 kV machine designed by BBC in 1930.

7 Cable-wound high-voltage motor as used to power the Troll platform in the North Sea

Synchronous machines with super-conducting excitation windings will perhaps be the next major step in electrical machine development.

Attempts have been made from time to time over the last decades to develop synchronous machines with super-conducting excitation windings. High-temperature super-conductors, cooled by liquid nitrogen, have recently renewed the interest in such machines, and it will perhaps be the next major step in electrical machine development. However, such machines are still far away from being commercial, and the development of more cost-effective, traditional-type synchronous machines continues.

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Further reading
Eriksson, S. (2007). *Electrical machine development: A study of four different machine types from a Swedish perspective.* Royal Institute of Technology, Stockholm.

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