ABB review

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The corporate technical journal

The city lights adorning the cover of this edition of *ABB Review* illustrate mankind's dependence on electricity. Electric light is probably even the most visible sign of human activity when our planet is seen from space. Electricity is involved in almost every aspect of economic activity. The delivery chain of the future, ranging from generation to consumption, must meet the four challenges of capacity, reliability, efficiency and sustainability. These four aspects lie at the heart of ABB's vision of smart grids.

Contents

Smarter grids

Dear Reader,

A modern business paradigm advises us to "work smarter, not harder." Time and energy invested in analyzing the way we work often yield greater gains than intensifying our efforts without changing our approach. What is true for one's personal situation is equally applicable to larger systems. In the case of transmission and distribution networks, changes in the way the grid is being used are raising the question of how best to handle these changes. Is it acceptable to require existing infrastructure to "work harder," ie, closer to the limits of existing equipment, thus exposing customers to an increased risk of failures and blackouts? Or is a "smarter grid" the better solution?

Overall consumption is rising, and the combined effects of market liberalization and the growing share of renewables are further adding to the stress on the grid. The availability of wind and solar energy is by nature intermittent and difficult to predict. Furthermore, renewable energy is often generated in remote locations where local grid infrastructure is weak. The roles of consumers and of the distribution grid are being redefined: Consumers with their own local generation are evolving to become "pro-sumers." The former distribution grid is thus also becoming a collection grid for distributed generation.

The traditional "work harder" approach would imply meeting the growth in variability with an increase in spinning reserves. This is not only costly but can partly negate the environmental advantage of renewable generation. The "work smarter" approach takes a more comprehensive view of the transmission system. Whereas the control system of a traditional grid assumes the demand side to be a "given," smart grids will increasingly incentivize consumers to modify their consumption patterns to suit availability.

A control system's ability to make optimal decisions depends on its accurate and up-to-date knowledge of the system status. Obtaining data starts with sensors at strategic locations on the grid. Although sensors will grow in their ubiquity, it is surprising how much data is already available in existing equipment. So besides adding further sensors, smart grids must address the communication needed to share this data, and indeed the control nodes that must act on it.

Some of these topics were discussed in the 3/2009 edition of *ABB Review* (Delivering power). The present issue builds on this, taking a comprehensive look at all major aspects involved in smart grids. For the generation side, HVDC Light® technology is used to connect wind farms, and at the same time improve the stability of the grid through its reactive-power control capability. A pioneering storage technology is also presented, offering short-term protection against variability.

On the operations and control side, a series of articles looks at improvements in network management software and technology. The best of control systems is of little use, however, if equipment does not perform as expected. We address service and maintenance for transformers, and also improvements in medium-voltage switchgear.

Moving on to the domestic perspective, smart meters give residents immediate feedback on their energy use and also facilitate the billing models that incentivize a reduction of peak loads. Finally, an intuitive control system helps home owners save energy.

I trust this issue of *ABB Review* will highlight ABB's ability to support all stakeholders – from transmission operators to home owners – in meeting the challenges of the smart grid.

Enjoy your reading.

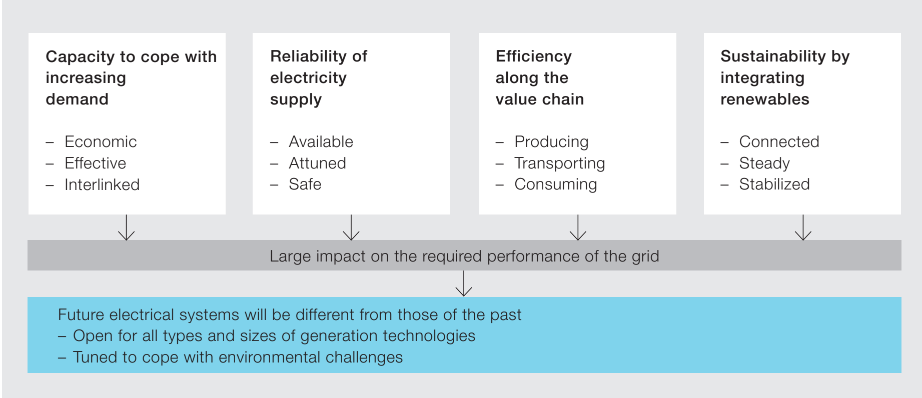
Peter Terwiesch
Chief Technology Officer
ABB Ltd.

Smart electricity

Efficient power for a sustainable world

BRICE KOCH, BAZMI HUSAIN – Electricity is the most versatile form of energy used around the world. The infrastructure necessary to generate, transmit, distribute and consume electricity was conceived and designed more than 100 years ago and ABB has been at the forefront of technological innovations for electrical infrastructure from the very beginning. This infrastructure has served us well and has been a significant contributor to the industrialization and economic growth of the world in the last few decades. There is hardly any process in industry or any application in private life that does not use electricity. The demand for electricity is growing faster than any other form of energy in all parts of the world – most notably in countries undergoing rapid industrialization, such as China and India. At the same time, increasing digitization of economies is placing higher demands on the reliability of electric supply – even momentary disruptions cause huge economic losses.

Smart grid value proposition – four main areas of emphasis



A sobering fact today is that coal fuels more than 40 percent of the world's electric supply, making electricity generation the single largest and fastest rising contributor to CO_2 emissions. This fact combined with the growing need for electricity is driving a fundamental and exciting change in the electrical industry.

To successfully address the challenges new solutions are needed along the electrical value chain – generation must increase but at the same time contribute less to greenhouse gas emissions. Transmission, distribution and consumption of electrical energy must become more efficient.

Today, the way electrical energy is generated, transported and used is not efficient enough. Inefficiencies along the whole value chain lead to around 80 percent of losses from the primary energy sources to the useful consumption of electricity.

Although the growth rate of renewable energy generation is high, the contribution of renewable energy in the overall energy mix is still quite small. Renewable energy, especially that originating from intermittent and variable sources (eg, wind and solar) pose additional challenges. Not least of these is availability, which highlights the need for energy storage as well as systems to coordinate available sources of power generation with sinks of consumption. To integrate the growing amount of renewable energy generation and, at the same time, significantly improve efficiency along the value chain, requires massive changes in the whole electrical system and the way it should be structured and operated.

This future evolving system has been coined by the term "smart grid".

Smart grids

The future electrical system (or smart grid), must be designed to meet four major requirements of the global society:

– Capacity
– Reliability
– Efficiency
– Sustainability

Capacity

As long as societal will does not limit the growth of energy consumption, it is expected that the consumption of electrical energy will grow substantially in the future. If the forecast of the International Energy Agency holds, it means that we will need to add one 1 GW power plant and related grid infrastructure every week for the next 20 years. The future electric system must cope with this capacity increase in an economic way.

Reliability

The larger the amount of electricity transported the closer the system will operate to its stability limit. Yet blackouts or even smaller disturbances are becoming increasingly unacceptable.

Reliability of the electrical system has always been a priority to engineers and has improved dramatically over the last few decades. Nevertheless, electricity interruptions are still a real risk. Dramatic events such as massive rolling blackouts that can cut a whole country from its electricity supply are only the small tip of a far larger iceberg. It is the large number of short disturbances that contribute to significant economic disadvantages. A recent study performed for the United States reported that unreliable electrical systems cost $80 billion annually [1].

Today coal fuels more than 40 percent of the world's electricity supply making electricity generation the single largest and fastest growing contributor to CO_2 emissions.

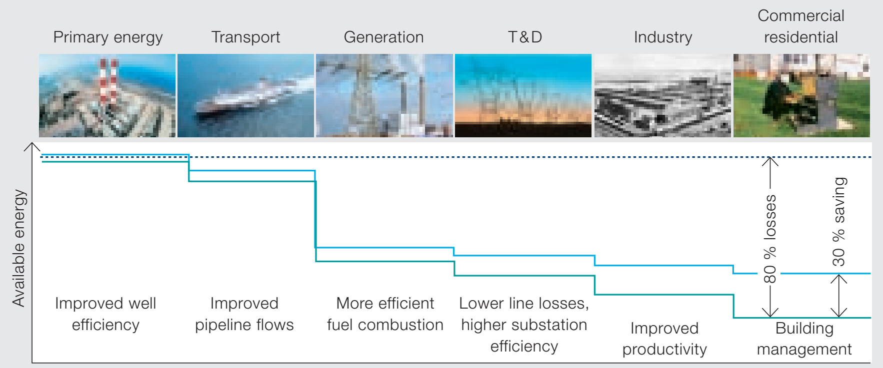
A more reliable electrical supply not only helps the economy and improves the quality of life, but it also has a positive influence on climate change. If an electrical system can safely handle and stabilize grid disturbances, then that system will require fewer generating plants available in reserve. This means lower emissions.

Energy efficiency

Projections by the International Energy Agency show that using energy more efficiently has a greater potential to curb CO_2 emissions over the next 20 years than all the other options put together [2].

Yet out of the financial sector's $119 billion invested in clean energy around the

Efficient generation, transport and better utilization of electricity



– Up to 80 percent losses along the energy value chain
– Some losses inherent to the generation of electricity

Energy efficiency along the value chain can reduce losses by 30 percent

A more reliable electrical supply not only helps the economy and improves the quality of life, but it also has a positive influence on climate change.

world in 2008, just $1.8 billion was spent on improving energy efficiency, according to a study by the UN Environment Program and New Energy Finance [3].

The reluctance to invest in energy efficiency is surprising. Investments can usually be recouped through lower energy costs in less than two years, and under other circumstances, businesses would normally leap at such prospects of rapid returns. A major obstacle is a lack of knowledge in private households, companies or public authorities concerning energy-efficient equipment. This challenge is further compounded by the variety of available options.

Another obstacle is a lack of incentives. Why should a landlord invest in energy efficiency if the tenant will reap the benefits? Why should a purchasing manager spend more of his budget on efficient equipment if the savings all go to the department that pays the electricity?

In addition, energy efficient solutions are rarely photogenic, and many have obscure names. Variable-speed drives, which raise the efficiency of electric motors, sit in plain metal boxes, belying the fact that their energy saving potential is many times greater than the much touted compact fluorescent light bulb. The drive systems installed by ABB alone save as much as 170 million metric tons of CO_2 every year globally. This corresponds to 20 percent of all emissions in Germany.

The European Union took an important step in June 2009 when it set efficiency standards for most of the electric motors used in industrial applications. The move was barely noticed, yet it is expected to save 135 billion kilowatt-hours per year by 2020. That is three times more than the savings expected from phasing out incandescent light bulbs in the European region and equals more than Sweden's total electric power consumption (which in 2007 amounted to 132 billion kWh).

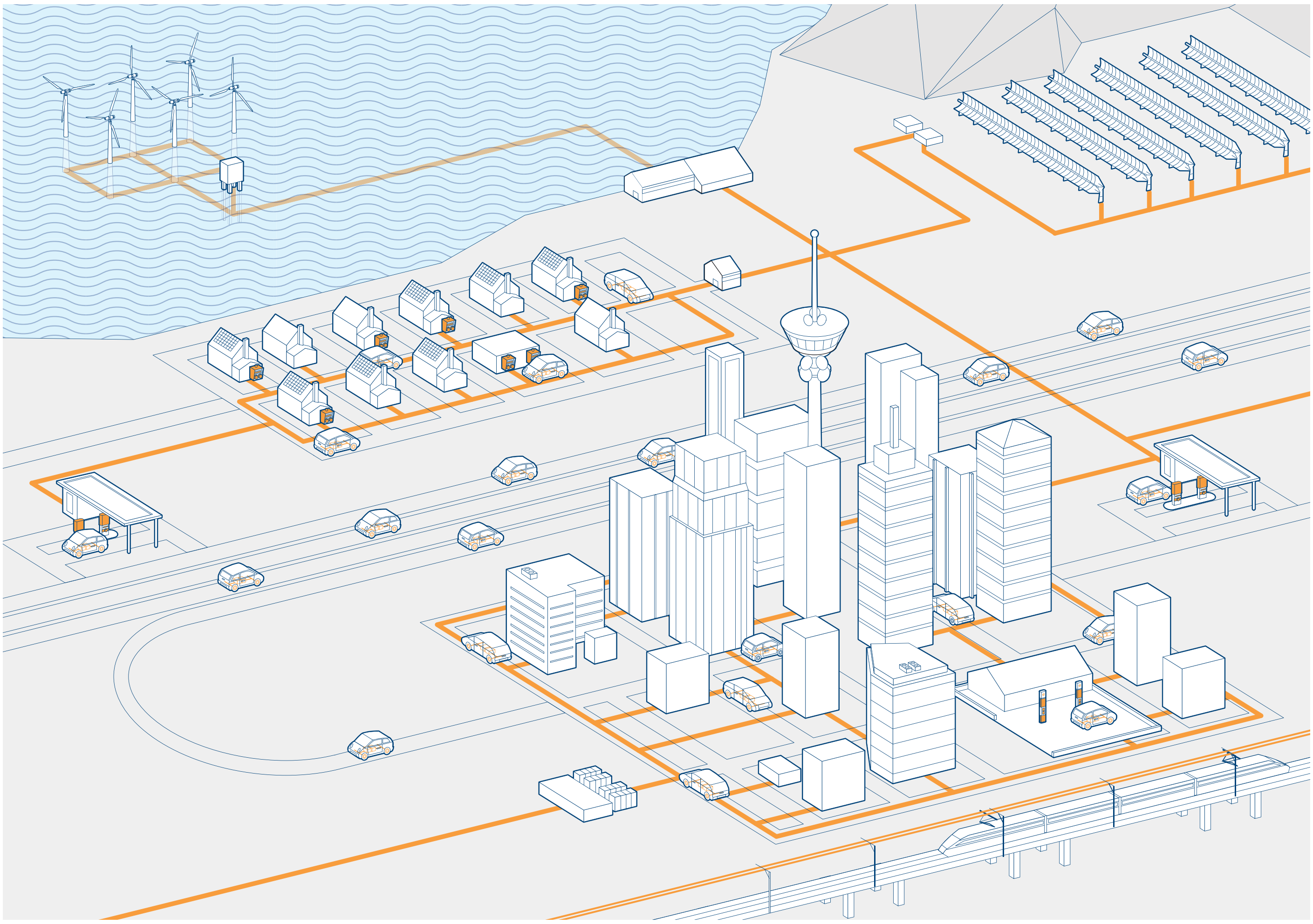
Sustainability

Generating electricity with solar, wind, wave or geothermal energy is without doubt a powerful way to avoid CO_2 emissions. There is hope that with improving technology, better conversion efficiency and sinking production costs, the contribution of such sources to the future energy mix will increase.

Hydropower is the traditional CO_2 free source of electrical energy and according to the IEA this will continue to be the case for the next 20 years.

Generating electricity in this way is one task; the other equally important requirement is to connect it to the electrical grid. Huge distances have to be bridged to carry electrical power from hydropower plants to the centers of consumption. In China, for example, bulk power is being transported more than 2,000 km with low transmission losses.

Intermittent wind-power generators pose another challenge on grid stability and the need for additional reserves, but adequate technology is also required to connect them from remote places far offshore. Energy storage will ultimately help



to overcome the issues of intermittency and HVDC cable technology is the way to cross the sea.

The final influence, however, is the end consumer who decides how much and in which way he wants to consume energy. At the present energy costs and in view of the difference between high and low tariffs, the incentives to save energy or use it at times of lower cost are limited. Technology could provide greater transparency regarding consumption at any moment in time and its associated cost to the consumer. The resulting demand-response relationship between generators and consumers makes a further contribution to the reduction of the required generating reserve.

ABB has the full portfolio of products, systems and services to further improve and develop the electrical system. Wide-area control systems, flexible AC transmission systems, substation control, HVDC systems, cable connections, distribution control and low-voltage systems address the grid. Drive systems, efficient devices and a broad application of process control technologies help to increase the efficiency in industrial and commercial applications. Building automation and control is another area with energy saving potential served by ABB. ABB meters and the connected communication technology that facilitates demand-response interactions and the software to operate energy markets is in use in many locations worldwide.

ABB is committed to lead further development of smart electricity, providing efficient power for a sustainable world.

> Generating electricity with solar, wind, wave or geothermal energy is without doubt a powerful way to avoid CO_2 emissions.

Brice Koch
Executive Vice President & Member
of the Group Executive Committee
Head of Market and Customer Solutions
ABB Asea Brown Boveri Ltd.
Zurich, Switzerland
brice.koch@ch.abb.com

Bazmi Husain
Head of ABB's Smart Grid Initiative
ABB Smart Grids
Zurich, Switzerland
bazmi.husain@ch.abb.com

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[1] Lawrence Berkeley National Laboratory (2005, February 11). Berkeley lab study estimates $80 billion annual cost of power interruptions.
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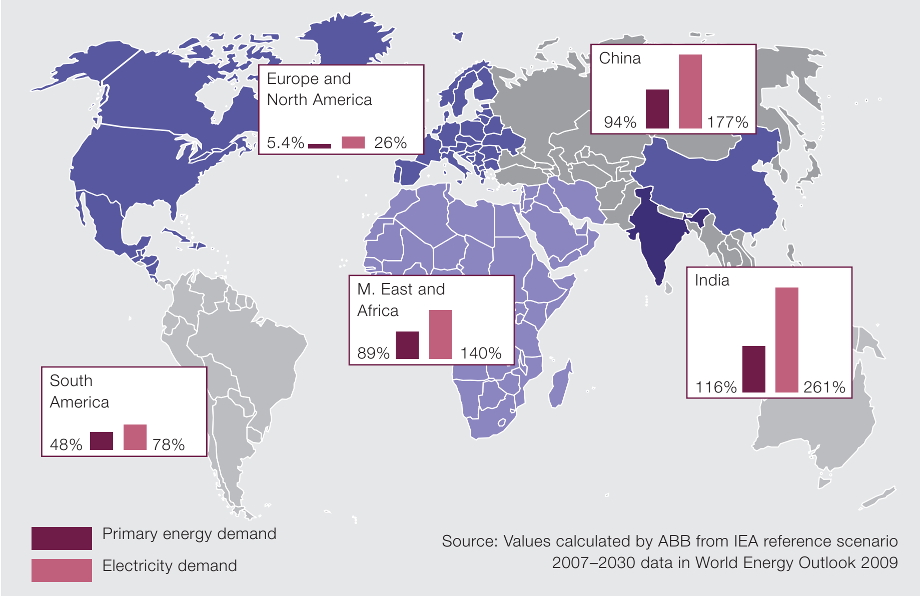
[3] UNEP and Global Energy Finance (2009, July). Global trends in sustainable energy investment 2009.

The next level of evolution

Smart grid technologies are key to supplying the world with high quality, clean, reliable and sustainable power

ENRIQUE SANTACANA, BAZMI HUSAIN, FRIEDRICH PINNEKAMP, PER HALVARSSON, GARY RACKLIFFE, LE TANG, XIAOMING FENG – Electrical power grids are critical infrastructures in all modern societies. However, many are aging and are stressed by operational scenarios and challenges never envisioned when the majority of the grids were developed many decades ago. These grids now need to be transformed into smart grids in order to meet the challenges facing developed and developing countries alike, such as the growing demand for electric power, the need to increase efficiency in energy conversion, delivery, consumption, the provision of high quality power, and the integration of renewable resources for sustainable development. The term smart grid has been frequently used in the last few years in the electric power industry to describe a digitized version of the present day power grid. Smart grids can be achieved through the application of existing and emerging technologies. However, it will take time and many technical and non technical challenges, such as regulation, security, privacy and consumer rights need to be overcome.

1 A demand growth comparison of primary and electrical energy



At the National Governors Association Convention in the United States in February 2009, the CEO of a major utility started his speech with the confession that he didn't really know what the term smart grid [1] meant [1]. Shocking as it may seem, such a confession may have absolved many in the engineering community who secretly felt the same way.

The definition of a smart grid may vary depending on where you are in the world. In the United States, for example, the following attributes are commonly cited as being necessary to define a smart grid [2–6]:

- It should be self-healing after power disturbance events.
- It should enable active participation by consumers in demand response.
- It should operate resiliently against physical and cyber attacks.
- It should provide quality power to meet 21st century needs.
- It should accommodate all generation and storage options.
- It should enable new products, services and markets.
- It should optimize asset utilization and operating efficiency.

According to a European Commission report [7], a smart grid in Europe is described as one that is:

- Flexible: It should fulfill customers' needs while responding to the changes and challenges ahead.
- Accessible: Connection access to all network users should be possible. In particular the smart grid should be accessible to renewable power sources and high efficiency local generation with zero or low carbon emissions.
- Reliable: This means the grid is secure and the quality of the supply is assured. It should be consistent with the demands of the digital age and resilient to hazards and uncertainties.
- Economical: The best possible value is provided through innovation, efficient energy management and a level playing field in terms of competition and regulation.

China, one of the biggest power-hungry economies on the planet, is also developing the smart grid concept. According to a memo issued by the joint US-China cooperation on clean energy (JUCCCE) in December 2007, "the term smart grid refers to an electricity transmission and distribution system that incorporates elements of traditional and cutting-edge power engineering, sophisticated sensing and monitoring technology, information technology and communications to provide better grid performance and to support a wide range of additional services to consumers. A smart grid is not defined by what technologies it incorporates, but rather by what it can do" [8].

The need for smart grids

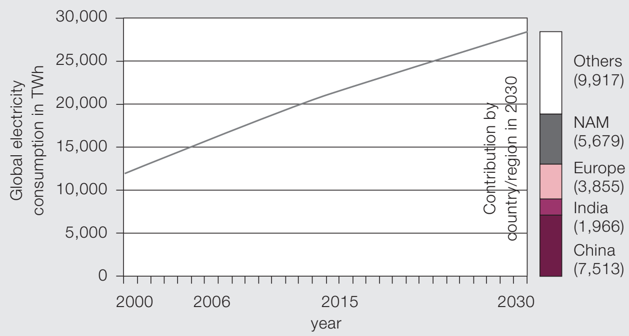
Electricity is the most versatile and widely used form of energy in the world. More than five billion people worldwide have access to electrical energy and this figure is set to increase. The level of electrical power consumption, reliability, and quality has been closely linked to the level of economic development of a country or region. According to an International Energy Agency (IEA) forecast, the worldwide demand for electrical energy is growing twice as fast as the demand for primary energy ➔ 1, and the growth rate is highest in Asia ➔ 2. Meeting this rise in demand will mean adding a 1 GW power plant and all related infrastructure every week for the next 20 years!

At the same time, an increasingly digitalized society demands high power quality and reliability. Simply put, poor reliability can cause huge economic losses. To illustrate this point, a Berkley National Laboratory report in 2005 stated that in the United States the annual cost of system disturbances is an estimated $80 billion, the bulk of which ($52 billion) is due to short momentary interruptions. The reported number of system disturbances from 2002 to the middle of 2008 is shown in ➔ 3. In addition, the threat of terrorist attacks on either the physical or cyber assets of the grids also heightens

Footnote

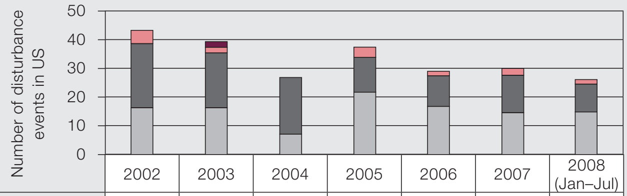
1 The term smart grid is sometimes interchanged with the terms intelligent grid, modern grid and future grid.

2 Global and regional electricity consumption



Source: IEA reference scenario in World Energy Outlook 2009

3 Reported disturbance events in the United States between 2002 and 2008



	2002	2003	2004	2005	2006	2007	2008 (Jan–Jul)
Category 5	0	1	0	0	0	0	0
Category 4	4	2	0	3	1	2	1
Category 3	22	20	19	12	11	13	10
Category 2	17	16	8	22	17	15	15

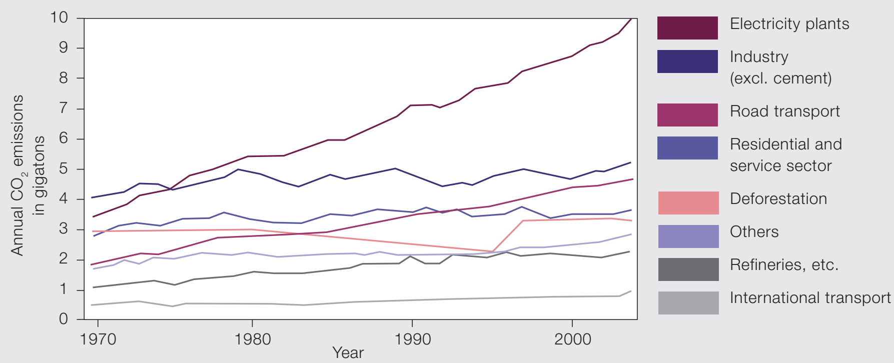
Source: NERC annual report 2008

the need for power grids that are more resilient and capable of self healing.

The impact on the environment is another major concern. CO_2 is responsible for 80 percent of all greenhouse gas effects and electric power generation is the largest single source of CO_2 emissions. The growth trend of annual CO_2 emissions (in gigatons) from electric power plants compared with the emissions from other sources is shown in ➔ 4. Shockingly, more than 40 percent of the CO_2 emissions from power plants are produced by traditional power plants. To reduce this carbon footprint while satisfying the global need for increased electrical energy, renewable energy, demand response (DR), efficiency and conservation will be needed. However, the increasing penetration of renewable energy brings with it its own challenges; for example, not only is the uncertainty in the supply increased but the remote geographical locations of wind farms and solar energy sources stress existing infrastructures even more.

These new requirements can only be met by transforming existing grids, which, for the most part, were developed many decades ago and have been showing signs of aging under increased stress. The growing consensus and recognition among the industry and many national governments is that smart grid technology is the answer to these challenges. This trend is evidenced by the appropriation – toward the end of 2009 – of more than $4 billion by the US government in grants to fund research and development, demonstration, and the deployment of smart grid technology and the associated standards [9]. The European union (EU) and China also announced major initiatives for smart grid technology research, demonstration and deployment in 2009.

4 Growing carbon footprint in which electrical power generation is the largest single source of CO_2 emissions



Source: IPCC "Migration of Climate Change," Cambridge University Press, 2007

Smart grid challenges

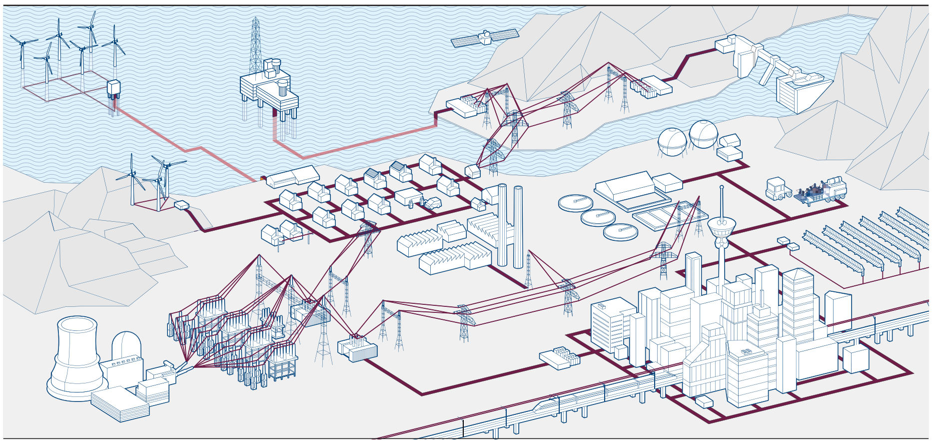
The main challenges facing smart grids, ie, doing more with less and improving efficiency, reliability, security and environmental sustainability, will depend on a combination of sensor, communication, information and control technologies to make the whole grid, from the entire energy production cycle right through to delivery and utilization, smart ➔ 5.

The most urgent technical challenges include:

- The economic buildup of grid capacity while minimizing, as much as possible, its environmental impact.
- Increasing grid asset utilization with power flow control and management.
- Managing and controlling power flow to reduce power loss and peak demand on both the transmission and distribution systems.
- Connecting renewable energy resources from local and remote

According to an International Energy Agency (IEA) forecast, the worldwide demand for electrical energy is growing twice as fast as the demand for primary energy.

5 Smart grid covers the entire generation, delivery and utilization cycle



6 Smart grid technology categories

- Decision intelligence
- Communication
- Sensor/Actuator
- Power conversion/transport/storage/consumption

7 Application examples controlled from within the decision intelligence layer

- Microgrid control and scheduling
- Intrusion detection and countermeasures
- Equipment monitoring and diagnostic evaluation
- Wide-area monitoring, protection and control
- Online system event identification and alarming
- Power oscillation monitoring and damping
- Voltage and var optimization
- Voltage collapse vulnerability detection
- Intelligent load balancing and feeder reconfiguration
- The control of a self-setting and adaptive relay
- End-user energy management
- Dynamic power compensation using energy storage and voltage-source inverters

locations to the grid and managing intermittent generations.

- Integrating and optimizing energy storage to reduce capacity demand on grids.
- Integrating mobile loads, (for example, plug-in electrical vehicles) to reduce stress on the grid and to use them as resources.
- Reducing the risk of blackouts; and when one has occurred, detecting and isolating any system disturbances and the quick restoration of service.
- Managing consumer response to reduce stress on the grid and optimize asset utilization.

Smart grid technology components

A smart grid consists of technologies, divided into four categories, that work together to provide smart grid functionalities ➔6. The bottom or physical layer is analogous to the muscles in a human body and it is where energy is converted, transmitted, stored, and consumed; the sensor and actuator layer corresponds to the sensory and motor nerves that perceive the environment and control the muscles; the communication layer corresponds to the nerves that transmit the perception and motor signals; and the decision-intelligence layer corresponds to the human brain.

The decision intelligence layer is made up of all the computer programs that run in a relay, an intelligent electronic device (IED), a substation automation system, a control center or enterprise back office ➔7. These programs process the information from the sensors or the communication and IT systems, and produce either the control directives or information to support business process decisions. These control directives, when executed by actuators, effect changes in the physical layer to modify the output from power plants and the flows on the grid.

The importance of decision intelligence and the actuator system in smart grids cannot be overstated; without controllable grid components to change the state of the power grid to a more efficient and reliable one, all data collected and communicated will be of very limited value. The more the output of power plants, the power flow on transmission lines and the power-consumption level of consumers are controlled, the more efficient and reliable grid operation can be. If, for example, the power flow control capability offered by flexible AC transmission system (FACTS) technology wasn't available, an independent system operator (ISO) would not be able to relieve transmission congestions without resorting to less economical dispatch plans. Or without the ability to control devices such as transformer tap changers or automatic switched capacitor banks, the industry will not even contemplate the development of voltage and var optimization control to reduce power loss.

For the decision intelligence layer to work, data from the devices connected to the grid need to be transmitted to the controllers – most likely located in the utility control center – where it is processed before being communicated back to the devices in the form of control directives. All of this is accomplished by the communication and IT layer, which reliably and securely transmits information to where it is needed on the grid.

However, device-to-device (for example, controller-to-controller or IED-to-IED) communication is also common as some real-time functionality can only be achieved through inter-device communications. Interoperability and security is essential to assure ubiquitous communication between systems of different media and topologies and to support plug-and-play for devices that can be automatically configured when they are connected to the grid.

Smart grid solutions

Smart grids will be built with existing and emerging technologies. ABB has been at the forefront of smart grid technology development long before the term was even coined, and the following examples support this claim.

Wide area monitoring system (WAMS)

ABB's WAMS collects information about grid conditions in real time at strategic locations. Accurate time stamps are provided by GPS satellite. It performs enhanced network analysis, incorporating phasor data to detect any instability. WAMS technology was recognized by the Massachusetts Institute of Technology (MIT) in 2003 as one of the 10 technologies that can change the world.

Supervisory control and data acquisition systems (SCADA)
SCADA systems monitor and supervise thousands of measuring points in remote terminals on national and regional grids. They perform network modeling, simulate power operation, pinpoint faults, preempt outages and participate in energy trading markets. With over 5,000 installations worldwide – more than any other supplier – the largest system in the world can be found in Karnataka, India and was delivered by ABB. It has 830 substations that supply electrical power to 16 million people ➔ 8. The system can increase operation efficiency by 50 percent and reduce "customer minutes lost" by 70 percent.

FACTS that improve power transfer
FACTS devices compensate the line inductance for maximum power transfer (series compensation) and provide power flow control capability. In some cases power system transmission capacity can even be doubled. They also mitigate disturbances and stabilize the grid (through dynamic shunt compensation). The world's largest static var compensator (SVC), with an operating range of + 575 MVAr (capacitive) to – 145 MVAr (inductive) at 500 kV is located at Allegheny Power (in the United States) and was delivered by ABB. In total, the company has installed over 700 systems, or more than 50 percent of all global installations.

High-voltage DC systems (HVDC)
HVDC systems convert AC from power generation to DC for transmission before reconverting back to AC for consumer use. Grids running at different frequencies (50 or 60 Hz) can therefore be coupled, while instabilities on one part of the grid can be isolated and contained. HVDC is ideal for transporting power from challenging locations (eg, subsea) and over long distances with low losses; for example, by installing an ultra high-voltage direct current (UHVDC) connection, as is the case with the 2,000 km link between Xiangjiaba and Shanghai in China, it is envisioned that transmission losses will be reduced by over 30 percent! One of the world's longest and most powerful transmission systems, supplied by ABB, transports 6,400 MW and operates at ± 800 kV.

HVDC also incurs lower infrastructure costs (fewer and smaller pylons and fewer lines) and this offsets the higher investment needed in converter stations. With more than 50 years experience in HVDC technology, ABB is widely recognized as the market and technology leader in this area.

Fault detection and system restoration
A substation automation system is a key component of ABB's smart grid portfolio. It performs data acquisition, remote communication, supervision control, protection and fault evaluation. ABB's substation automation systems are compliant with the IEC 61850 communication standard to assure interoperability with similar compliant products. With more than 700 such systems sold to date, one of the world's largest substation automation systems, installed by ABB, is situated in Moscow.

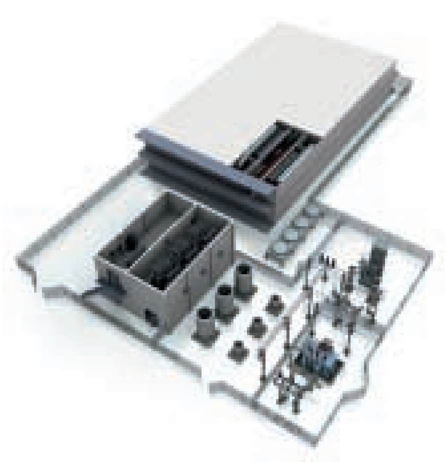
Process control in power generation
The optimization of auxiliary systems in power plants offers significant savings when one considers that up to 8 percent of a plant's production may be consumed by these systems. Additional savings can be realized by improving both the combustion system process and start-up times for boilers. Savings in both thermal and electrical energy can be achieved using existing ABB technologies.

Driving toward industrial efficiency
The optimization of motor-driven systems offers the single largest energy-saving potential in industry. The installation of drive systems alone could save around 3 percent of energy, equivalent to the output from more than 200 fossil power plants (each producing 500 MW). The global installed base of ABB drives provides an annual saving of 170 million tons of CO_2, which corresponds to 20 percent of total emissions in Germany. Process control is another effective and immediate way for industry to achieve energy savings of approximately 30 percent using existing ABB technologies.

Building control for optimal performance
According to the World Business Council for Sustainable Development (WBCSD), automation systems installed in buildings can reduce energy consumption by up to 60 percent, while global consumption could fall by as much a 10 percent. ABB building control systems allow the individual adjustment of rooms and appliances to ensure energy consumption is at its most efficient. For example, using

8 The control room at Karnataka Power

9 An impression of an SVC Light® with Energy Storage installation



Smart grid technology is not a single silver bullet but rather a collection of existing and emerging technologies working together.

ABB's i-bus/KNX technology, which is used in hotels, airports, shopping centers and houses around the world, energy consumption was reduced by 30 percent in several large buildings in Singapore.

ABB has been at the forefront of smart grid technology development long before the term was even coined.

Solar and hydropower

ABB supplies power plant control for hydro, wind and solar plants, as well as tailor-made long-distance connections to integrate green energy sources to the grid. Such an automation system and associated electrical equipment has already been delivered to Europe's first large-scale 100 MW solar plant in Spain (Andasol). In Algeria, the complete plant control for the world's first integrated solar combined cycle plant (175 MW) has also been supplied by ABB, while a turnkey 1 MW solar concentration plant, with a performance ratio of 80 percent, was constructed in Spain in record time. To date, ABB has connected 230 GW of renewable energy to the grid.

Offshore wind parks

ABB is the world's largest supplier of electrical equipment and services to the wind energy industry. It supplies complete electrical systems for wind generation as well as subsea connections to onshore grids. HVDC Light®, with its oil-free cables and compact converter stations, will connect the Borkum offshore wind park, one of the world's largest with a capacity of up to 400 MW and located 125 km out to sea, to the German national grid.

Energy storage to bridge outage periods

The total electrical power input and output on an interconnected grid must be closely balanced at all times. Any imbalance will cause the system frequency to deviate from the normal value of 50 or 60 Hz. Balancing power is a major issue for utilities and is especially critical as large amounts of intermittent wind and solar energy are added to the supply mix. Bulk storage of electrical energy helps to compensate for any imbalance in the system and reduces the need for expensive spinning reserve capacities. Battery systems with DC to AC converters are one way of coping with the problem. The world's largest battery energy storage system [2] (BESS) is located in Fairbanks, Alaska and was installed by ABB. This installation can supply 26 MW of power for 15 minutes, giving the utility enough time to bring back-up generation on line in the event of an outage.

Integrating storage with FACTS

FACTS devices regulate power flow or voltage in a grid to maximize capacity by regulating the line's reactance or by injecting reactive power. By combining a battery storage system with FACTS (to create SVC Light® with Energy Storage [3]), active power can be injected or extracted as needed and quickly ➔ 9. In addition, it provides power balancing, peak power support, and voltage and power quality control. This solution will be in operation in 2010. Future systems will operate in the MW range.

Building the grid of the 21st century

Smart grid technology is not a single silver bullet but rather a collection of existing and emerging technologies working together. When properly implemented, these technologies will increase efficiency in production, transport and consumption; improve reliability and economic operation; integrate renewable power into the grid; and increase economic efficiency through electricity markets and consumer participation. A century of technological leadership has equipped ABB with a broad portfolio of products and systems that will be called upon to build and operate the smart grids of the 21st century.

Footnotes

2 BESS comprises a massive nickel-cadmium battery, power conversion modules, metering, protection and control devices, and service equipment. In operation, BESS produces power for several minutes to cover the time between a system disturbance and when the utility is able to bring backup generation online.

3 For more information, refer to "Storage for stability: The next FACTS generation" on page 24 of this issue of *ABB Review*.

Enrique Santacana
President & CEO, ABB Inc.
Cary, NC, United States
enrique.santacana@us.abb.com

Bazmi Husain
Friedrich Pinnekamp
ABB Smart Grids
Zurich, Switzerland
bazmi.husain@ch.abb.com
friedrich.pinnekamp@ch.abb.com

Per Halvarsson
ABB Power Systems, Grid Systems/FACTS
Västerås, Sweden
per.halvarsson@se.abb.com

Gary Rackliffe
ABB Power Products
Raleigh, NC, United States
gary.rackliffe@us.abb.com

Le Tang
Xiaoming Feng
ABB Corporate Research
Raleigh, NC, United States
le.tang@us.abb.com
xiaoming.feng@us.abb.com

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The power to change

Stabilizing grids and enabling renewable power generation with PCS 6000 STATCOM

TOBIAS THURNHERR, CHRISTOPH G. SCHAUB – Our future energy mix will rely on the addition of a combination of renewable sources, such as hydro, wind, solar and tidal energy. This means the electricity grid must be adapted so that it can first cope with these additional sources of generation and second, use them in the most optimal way possible. On the distribution side, renewable power generation units must be modified so that the electricity they feed into the grid is as reliable as the electricity supplied by conventional power generators. To maintain efficient transmission and distribution, the reactive power balance in a system needs to be controlled. Inefficient reactive power management can result in high network losses, equipment overloading, unacceptable voltage levels, voltage instability and even outages. ABB offers a comprehensive range of reactive power compensation products and customized solutions to meet these challenges. One such solution, the PCS 6000 STATCOM (Power Converter System 6000 Static Synchronous Compensator), is proving to be a reliable, robust and efficient addition to a wind farm in the UK.

Living standards and energy consumption are growing from year to year. According to a MAKE Consulting market outlook, the worldwide demand for power will increase by 79.6 percent between 2006 and 2030. This demand must be met by clean and renewable energy sources, since conventional fossil fuel power generation plants contribute greatly to greenhouse gas emissions and global warming.

In 2006, 18 percent of the power generated was derived from renewable resources, mainly hydroelectric generation. The scale of future renewable power generation and its overall share of the energy mix are difficult to predict since this depends largely on the political climate. However, if currently planned political initiatives are implemented the total share of renewable power generation is expected to rise to 23 percent by 2030; more optimistic forecasts have even suggested a 62 percent share.

No matter the predicted size of the renewable power sector, wind power generation will play a significant part in the future supply of power. In some countries, wind turbines already play a significant role in energy production, and in some regions, there is still space for new wind parks. Unfortunately, it is becoming increasingly difficult to find new areas in which to economically harvest wind energy, ie, to find areas that are accessible, where the wind blows steadily and where the visual impact is acceptable. Nevertheless, the potential for offshore installations is particularly large. Here the wind generally blows more steadily than on land and access is less restrictive.

> Wind power generation will play a significant part in the future supply of power and ABB's STATCOM can help support a stable power grid.

Connecting wind turbines to existing electricity grids presents quite a challenge. Because the environment determines the ideal location for a wind park, such locations tend to be far from existing transmission lines with sufficient spare capacity. Furthermore, wind-power generators frequently behave differently to conventional generators, such as thermal or nuclear power plants, in terms of reactive power output capability, frequency control and fault ride-through capability (ie, the ability to remain connected, supplying power to the electrical system immediately after a network fault). In areas where wind generators comprise a large share of the generation capacity, this can have a negative impact on the entire network's stability.

For this reason grid operators are forced to introduce technical standards, so-called "grid codes," which must be fulfilled so that permission can be granted for a wind park to join the grid.

Reactive power and voltage control

Contrary to electric power frequency, which has to be the same at every point of an interconnected grid, the voltage is a local parameter that varies depending on the location and load flow in the grid. In a circuit where the load is purely ohmic, the voltage and current waveforms are in phase and transmitted real power is at a maximum. However, the inductive nature of the grid means that the flow of electric current is altered so that the voltage and current waveforms are out of phase. In a circuit powered by a DC source, the impedance equals the total resistance of the circuit. In an AC powered circuit, however, the electric devices in the circuit, ie, inductors (generators and transformers), capacitors and even the transmission cable itself, contribute to the impedance (see Factbox 2 on page 35 of *ABB Review* 3/2009). Inductors and capacitors generate or consume reactive power, thereby creating current flows. To reduce the affects of this reactive power, devices with matching impedance should be located carefully on the grid to maximize the transfer of real power.

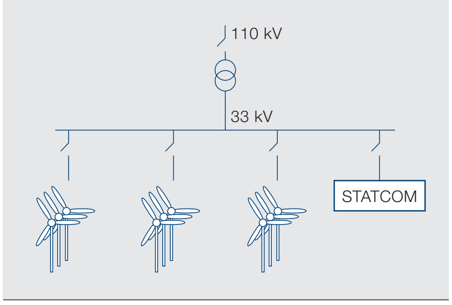
In areas requiring large amounts of reactive power, eg, areas of the grid with many asynchronous motors, the local voltage is reduced and a bank of capacitors should be introduced to match the impedance of the motors and maintain nominal voltage levels. Maintaining nominal voltage levels is important because most electrical components only tolerate small deviations in voltage. If the voltage is too low or too high the grid becomes unstable and components can malfunction or become damaged.

Besides affecting the voltage, reactive power flows also increase the load on transmission lines and transformers, thereby restricting their active power transmission capacity. By lowering the reactive current in transmission lines, capacity is increased and losses are reduced. This solution is faster and more cost effective than building additional transmission lines.

ABB offers a comprehensive range of reactive power compensation products and customized solutions to meet these challenges.

One such solution is the Power Converter System 6000 Static Synchronous Compensator, better known as the PCS 6000 STATCOM. The system meets the most stringent dynamic response requirements and is able to deliver full reactive current even during voltage dips, making it the perfect add-on solution for wind parks. It allows wind parks to meet highly demanding grid codes, stabilizes both positive and negative sequence voltages in industrial plants and provides

1 Schematic overview of the wind park



2 ABB STATCOM in a container version

reactive compensation for motor starting and dynamic voltage control in weak transmission grids.

ABB STATCOM

One of the first countries in which the grid operator introduced a grid code specifying the reactive power requirements for wind parks was the United Kingdom. Here several ABB STATCOMs are already in operation, statically and dynamically supporting the grid. Recently, a 24 MVAr STATCOM was installed and operates successfully to ensure that the Little Cheyne Court wind park, located near Rye in Kent in the southeastern part of the United Kingdom, fulfills the National grid code.

A typical wind park setup is shown in ➔ 1. The STATCOM in Little Cheyne Court is connected to the secondary side of the 110 kV / 33 kV wind park transformer. Here the STATCOM stabilizes the local voltage in the wind park by creating a voltage drop across the transformer. However, depending on the customer requirements or the grid code, the STATCOM could have been connected directly to the transmission level on the primary side of the wind park's main transformer.

Contrary to passive components, such as capacitors or inductors, the STATCOM can output its full reactive current even at low voltages and is limited only by the need for active power to cover its losses. The reactive power output capability of the system decreases linearly with the voltage, whereas for passive components, the reactive power output is proportional to the square of the voltage.

The PCS 6000 STATCOM consists of a voltage source converter, connected to the grid through a transformer. The converter contains so-called power electronic building blocks with integrated gate-commutated thyristors (IGCTs). Developed in the 1990's, IGCT's combine the advantages of insulated-gate bipolar transistors (IGBTs) and gate turn-off thyristors (GTOs), ie, low switching and conduction losses, fast switching capability and robustness. The same IGCT platform is used for medium-voltage drives, frequency converters feeding railway grids and full-power converters for large wind turbines. The IGCT allows high power density within a compact space, thereby reducing the overall footprint of the unit.

ABB's STATCOM is controlled by an AC 800PEC (power electronics controller) high-performance control unit, providing fast and precise closed-loop control and protection functions.

All STATCOM units are water cooled, with either an external water-to-air heat exchanger or a raw water cooling circuit. The water-cooling unit makes fans unnecessary, and thus reduces or even eliminates air exchange with the environment, preventing dust, sand particles and salt entering the converter. This in turn results in lower maintenance requirements.

The ABB STATCOM can be installed either in a building or in a cost-effective outdoor container ➔ 2. The container includes a cooling unit, a control system with a human machine interface (HMI), air conditioning for the control room and a heater for the converter room. It is fully wired and tested prior to delivery to reduce installation and commissioning time.

STATCOM control

ABB's STATCOM is controlled by an AC 800PEC (power electronics controller) high-performance control unit. This controller provides fast and precise closed-loop control and protection functions and coordinates slower processes, such as the supervision and control of the cooling unit and communication via a customer interface, all within a single unit.

The control system is setup in Switzerland before shipping. A downscaled hardware simulator allows extensive tuning and testing of the software before delivery, so that only minor fine-tuning is required during plant commissioning.

STATCOMs used for wind parks or in transmission grids usually run in a U-Q control mode. This means the grid operator specifies a certain set point voltage U0 and a slope N, as shown ➔ 3. The STATCOM measures the grid voltage and injects reactive power when appropriate, which varies linearly with the difference between the measured voltage and the set point voltage. If the measured voltage is below the set point voltage, the STATCOM acts like a capacitor bank and injects reactive power into the grid to support the grid voltage. If the measured voltage is greater than the set point voltage, the STATCOM acts as an inductor and suppresses the grid voltage. The slope defines the proportionality between the STATCOM output and the difference between the set point voltage and the measured voltage.

Harmonic characteristics

A grid-connected converter has to fulfill certain grid harmonic requirements, such as IEEE 519 or IEC 61000-2-12. Depending on the size of the unit, the multilevel topology allows the PCS 6000 STATCOM to fulfill these requirements without a harmonic grid filter. If desired, a suitable optional filter can be supplied,

> The STATCOM acts like a capacitor bank when the measured voltage is below the set point voltage and like an inductor when the measured voltage is above.

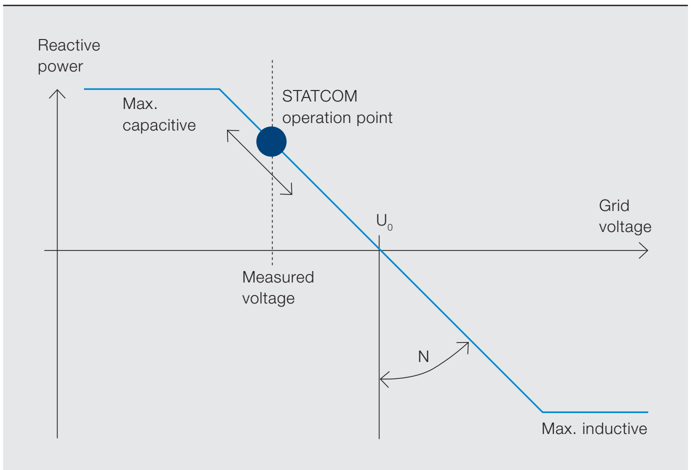
either to offset the reactive power output of the STATCOM or to filter certain harmonics already present in the grid.

A very valuable benefit of the ABB STATCOM is that its input impedance can be adjusted for a certain range of harmonics. This is extremely helpful for damping resonating systems. A sister installation of the Little Cheyne Court STATCOM is controlled such that the input impedance of the STATCOM is resistive for a given range of multiples of the fundamental frequency. This means that for this range of frequencies, the STATCOM absorbs energy from the grid and re-injects the energy back into the grid at the fundamental frequency. In this way, resonance in the wind park can be mitigated. A high-frequency oscillation would cause a harmonic fault in the turbine control and result in the immediate disconnection of turbines. ABB's STATCOM allows the wind park to generate clean power without having to wait for the delivery of passive components to solve the problem, as shown in → 4. The grid voltage, which is measured when the STATCOM is disconnected, is shown in → 4a. It is observed that a harmonic voltage is superimposed with the fundamental frequency voltage. → 4b shows how this harmonic voltage can no longer be seen when the STATCOM is connected.

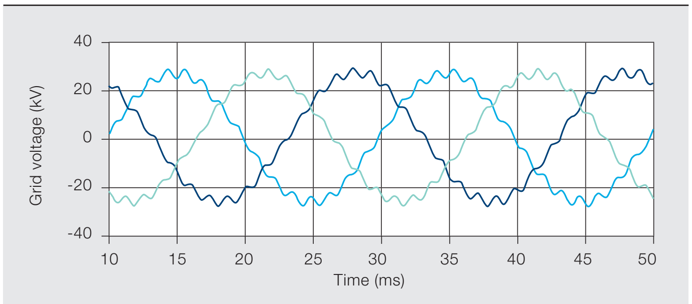
A successful solution

ABB's PCS 6000 STATCOM is a robust, reliable and efficient solution that is suitable as an add-on for wind parks to make them compliant with grid connection rules or as a fast and dynamic reactive power compensator for utilities. The demand for ABB's STATCOM will remain strong in a climate where the continuous and steady supply of electricity will have to be met through the expanded use of wind-powered turbines and other less reliable power sources, especially when the electricity grids of the future are extended into developing countries.

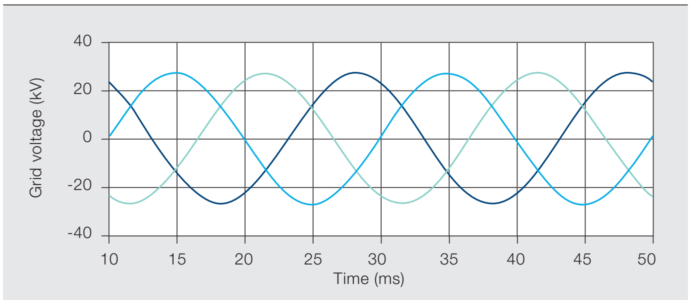
3 Typical control mode of the STATCOM



4 33 kV bus voltage in the wind park



4a without the STATCOM



4b with the STATCOM

Tobias Thurnherr

Christoph G. Schaub

ABB Discrete Automation and Motion

Turgi, Switzerland

tobias.thurnherr@ch.abb.com

christoph.g.schaub@ch.abb.com

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Sustainable links

HVDC is a key player in the evolution of a smarter grid

RAPHAEL GÖRNER, MIE-LOTTE BOHL – Today's electricity supply depends predominantly on large generating plants such as fossil fuel or nuclear facilities. Traditionally, the control strategy of transmission and distribution network operators builds on the controllable nature of these plants in matching the more inelastic and uncontrollable demand side. Increasing use of renewable energy sources such as wind and solar is changing this strategy. The availability of these new technologies is less controllable and predictable. Grids must hence be able to rapidly, reliably and economically respond to large and unexpected supply-side fluctuations. HVDC technology – in particular HVDC Light® – allows rapid and precise control of voltages and power flows. It is reliable and economical, and can be used to flexibly enhance existing AC grids. HVDC Light is also the first choice for transmitting power from large offshore wind farms to AC grids.

1 Drivers and HVDC applications

Drivers	Applications
Energy efficient bulk power long distance distance transmission	UHVDC, HVDC
Subsea transmission	HVDC, HVDC Light®
Connectiong renewable energy	Remote hydro: HVDC, UHVDC Offshore wind: HVDC Light DC grid (HVDC Light)
Grid reliability	HVDC Light
Difficult to build new transmission	HVDC Light underground transmission Converting AC OHL to DC OHL: HVDC, HVDC Light
Connecting networks Trading	Asynchronous connections HVDC, HVDC Light Back-to-Back

HVDC (High Voltage DC) technology can contribute toward future grids in many ways. These include:

Flexibility: It is well suited for quick responses to both operational changes and customer needs

Accessibility: It is accessible for all power sources, including renewable and local power generation

Reliability: It assures both quality of supply and resilience toward uncertainties and hazards affecting production of renewable energy.

Economy: It provides efficient operation and energy management, and the flexibility to adapt to new regulations.

In technical terms, HVDC technology supports:

- Load flow control
- Reactive power support
- Voltage control
- Power oscillations control
- Flicker compensation
- Voltage quality
- Handling of asymmetrical loads
- Handling of volatile loads

HVDC – a tool kit for smart transmission

ABB's HVDC technologies have been selected for some of the most demanding transmission schemes being realized today. These technologies, HVDC Classic and HVDC Light, are mainly differentiated according to their applications → 1.

HVDC Classic is primarily focused on long-distance, point-to-point bulk power transmission. A typical application can be the transmission of thousands of megawatts from remote hydro sources to load centers: For example the 800 kV Xiangjiaba-Shanghai link, which provides the capacity to transmit 6,400 MW over a distance in excess of 2,000 km. The link has an overall energy efficiency of 93 percent, yet its land use is less than 40 percent of that needed by conventional technology. At more than 99.5 percent, availability is also very high.

HVDC Light, on the other hand, is ideal for integrating dispersed, renewable generation, eg, wind power, into existing AC grids. It is also used for smart transmission and smart grids due to its great flexibility and adaptability.

The first HVDC link in the world to connect an offshore wind farm with an AC grid is the BorWin1 project. Based on HVDC Light technology, this 200 km link connects the Bard Offshore 1 wind farm off Germany's North Sea coast to the HVAC grid on the German mainland. This link transmits 400 MW at a DC voltage of ±150 kV and was ready for service in late 2009.

When complete, the wind farm BARD Offshore 1 will consist of 80 wind generators, each with a capacity of 5 MW. These will each feed their power into a 36 kV AC cable system. This voltage will then be transformed to 155 kV AC before reaching the HVDC Light converter station, located on a dedicated platform → 2. Here the AC is converted to ±150 kV DC and fed into two 125 km sea cables, which then continue into two 75 km land cables, transmitting 400 MW power to the land-based converter station at Diele in Germany.

The 800 kV DC link connecting Xiangjiaba with Shanghai can transmit a power of 6,400 MW over a distance of more than 2,000 km.

HVDC Light technology

HVDC Light is based on voltage source converter (VSC) technology. It uses IGBTs (insulated-gate bipolar transistors) connected in series to reach the desired voltage level. This technology is used for power transmission, reactive power compensation and for harmonics and flicker compensation.

Besides the converter itself, an HVDC Light station comprises AC and DC switchyards, filters and the cooling system. ABB's converter design ensures both steady-state and dynamic operation with extremely low levels of induced ground currents. This is a major advantage in an offshore environment, as it eliminates the need for cathodic protection as part of the installation.

The magnitude and phase of the AC voltage can be freely and rapidly controlled within the system design limits. This allows independent and fast control of both the active and the reactive power, while imposing low harmonic levels (even in weak grids).

Normally, each station controls its reactive power contribution independently of the other station. Active power can be controlled continuously and, if needed, almost instantly switched from "full power export" to "full power import." The active power flow through the HVDC Light system is balanced by one station controlling the DC voltage, while the other adjusts the transmitted power. No telecommunications are needed for power balance control.

From a system point of view, an HVDC Light converter acts as a zero-inertia motor or generator, controlling both active and reactive power. Furthermore, it does not contribute to the grid's short-circuit power as the AC current is controlled by the converter.

Offshore wind integration

An HVDC Light converter station's ability to enforce an AC voltage at any arbitrary value of phase or amplitude is of great value in starting an offshore network. Initially, the offshore converter operates as a generator in frequency-control mode, creating an AC output voltage of the required amplitude and frequency. The voltage is ramped up smoothly to prevent transient overvoltages and inrush currents. Finally, the wind turbine generators are automatically connected to the offshore network as they detect the presence of the correct AC voltage for a given duration. This functionality cannot be realized with classical thyristor-based HVDC transmission, as the latter would require a strong line voltage to commutate against.

2 BorWin alpha, the platform-based HVDC Light converter station

HVDC Light is ideal for integrating dispersed, renewable generation, eg, wind power, into existing AC grids.

An HVDC Light connection can similarly be used for network restoration after a blackout. As a blackout occurs, the converter will automatically disconnect itself from the grid and continue to operate in "house-load" mode. This is possible because the converter transformer is equipped with a special auxiliary power winding for the supply of the converter station.

Meeting strict grid codes

With globally installed wind power generation experiencing rapid growth, grid code requirements are becoming stricter. Most present grid codes set requirements on "fault ride through" or "low-voltage ride through," meaning that a wind turbine or park must be able to survive sudden voltage dips down to 15 percent (and in some cases down to zero) of the nominal grid voltage for up to 150 ms.

Often applications expect frequency response requirements (ie, the wind farm power output must rise in response to decreasing grid frequency and vice versa). In a wind farm connected via an HVDC Light transmission system, frequency response control can be implemented via a telecommunications link, which also transmits the momentary main grid frequency as well as other variables. Since the amplitude, frequency and phase of the voltage on the wind farm bus can be fully controlled by the converters, the grid frequency can be "mirrored" to the wind farm grid without any significant delay.

If a reduction in the main grid voltage occurs, power transmission capability is reduced correspondingly due to the current limit of the land-side converter. In a "standard" HVDC Light transmission system connecting two utility grids, a similar scenario is solved by immediately reducing the input power of the rectifying converter through closed-loop current control.

However, a reduction in input power of the offshore converter can cause the wind farm's bus voltage to increase notably, causing the converter and/or the wind turbines to trip. One possible solution is to use the wind farm's grid voltage to reduce generator output immediately.

Due to the link's low DC capacitance value, an interruption of power transmission can cause the DC voltage to rise to an unacceptably high level (such as to the 30 percent overvoltage level tripping limit) in just 5 to 10 ms. The wind turbine generators must be able to detect this condition and reduce their output power within this time frame. As an alternative, a DC chopper can be used to dissipate excess energy that cannot be transmitted by the inverting converter. This approach minimizes the risk of abrupt power changes from the wind turbines, and the disturbances to which they are exposed will be minimized.

Reducing the generator's power output is an effective method, but it is dependent on the response of the generators to voltage variations. A DC chopper, however, offers a more robust solution in that its operation is the same regardless of generator type. Furthermore, an HVDC Light link, combined with a chopper, decouples the wind park grid from the fault and electrical transients that occur in the main grid, thereby reducing the mechanical stresses on the equipment in the wind turbines.

> An HVDC Light converter station's ability to enforce an AC voltage at any arbitrary value of phase or amplitude is of great value in starting an offshore network.

This innovative HVDC Light solution is being supplied by ABB to the German TSO (Transmission System Operator) Transpower (formerly E.ON Netz) for what will be one of the largest offshore wind farms in the world. It is the first project in which offshore wind power is connected to the main AC grid using HVDC transmission.

HVDC Light technology features very low electromagnetic fields, oil-free cables and compact converter stations. Moreover, it cuts transmission losses by as much as 25 percent compared with traditional technology. This link will make an important contribution to Germany's goal of increasing the share of renewable energies in power generation from its current level of 15 percent to between 25 and 30 percent by 2030.

Building blocks for super grids

One of the key drivers of smart grids is the integration of renewable energy sources, especially offshore wind power, into the current HVAC grids. This has a huge environmental benefit, as it creates an opportunity to replace fossil fuel with renewable energy. Another benefit is that HVDC Light transmission technology is efficient and based on equipment manufactured with nonhazardous materials.

Future grids, combined with an efficient regulatory framework, will offer electricity customers more choices, increase competition between different providers and encourage innovative technology. As grids get smarter, availability and quality of power supply can be controlled in a much more efficient way supporting today's AC grids.

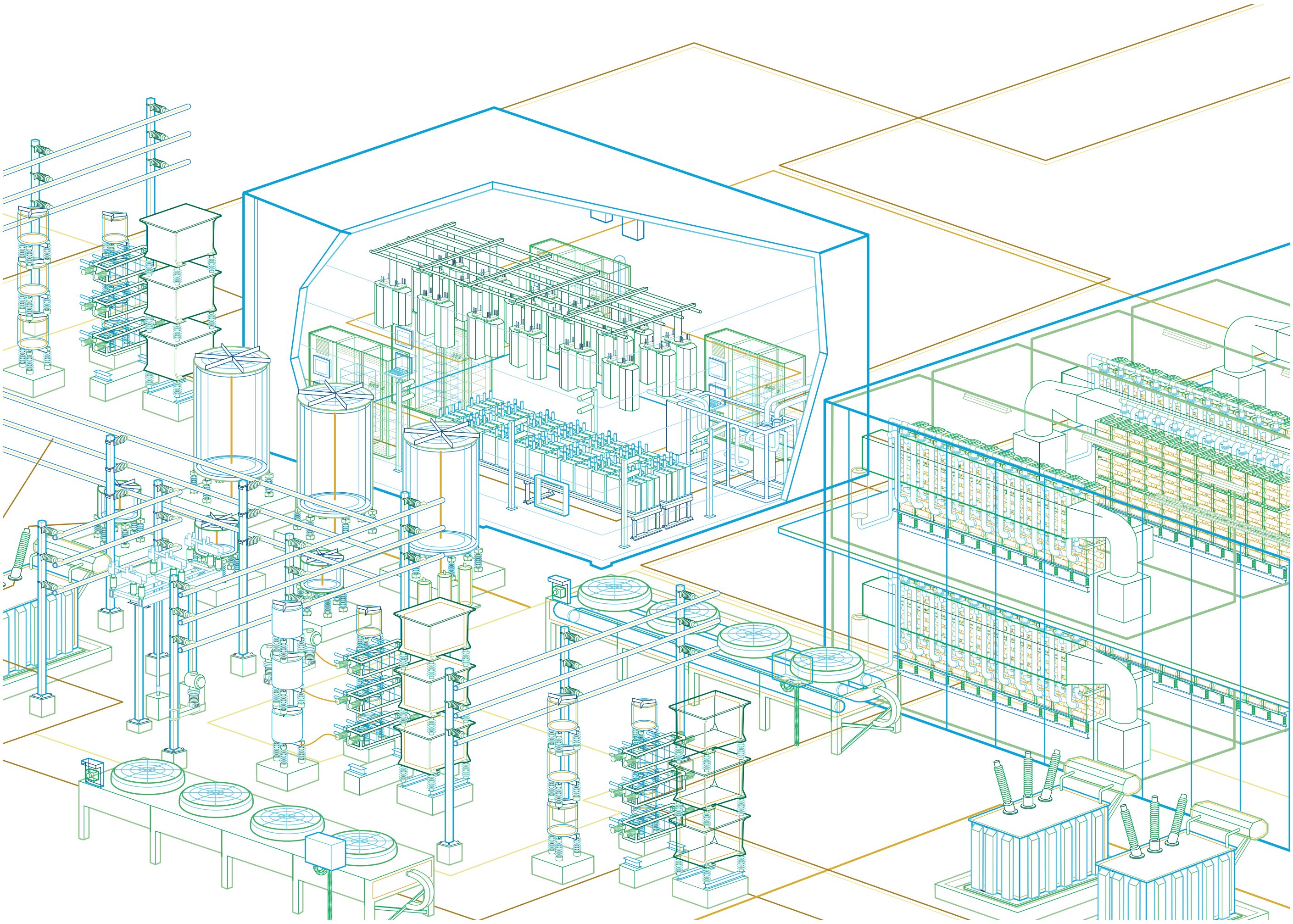
The recent HVDC Light project BorWin1 is an excellent example of a building block of the future grid. The combination of such offshore wind grid connections with interconnections for electricity trading between neighboring countries will also facilitate the development of so-called super grids. These overlaying DC grids, located either offshore or on land, will be able to feed large power volumes into existing AC grids.

As another example, the East-West Interconnector, a 500 MW, 200 kV transmission system connects the Irish and British HVAC grids. The distance between the respective converter stations is 250 km, with most of it covered by a 186 km sea cable under the Irish Sea, and the rest with short land cables. This transmission will be based on HVDC Light, and will become operational in 2012.

The effect of these building blocks in shaping the evolution of super grids is similar to the historic development of HVAC grids. A century ago, interconnections permitted local generation units and transmission lines to be combined into local grids, which in turn evolved as regional grids. Besides being more flexible and smarter, future grids will also be more reliable and efficient and offer a higher degree of control over generation, integration, consumption, grid voltages and power flows. HVDC will be a dominant enabling technology in realizing this vision.

Raphael Görner
ABB Power Systems, Grid Systems
Mannheim, Germany
raphael.goerner@de.abb.com

Mie-Lotte Bohl
ABB Power Systems, HVDC and FACTS
Ludvika, Sweden
mie-lotte.bohl@se.abb.com

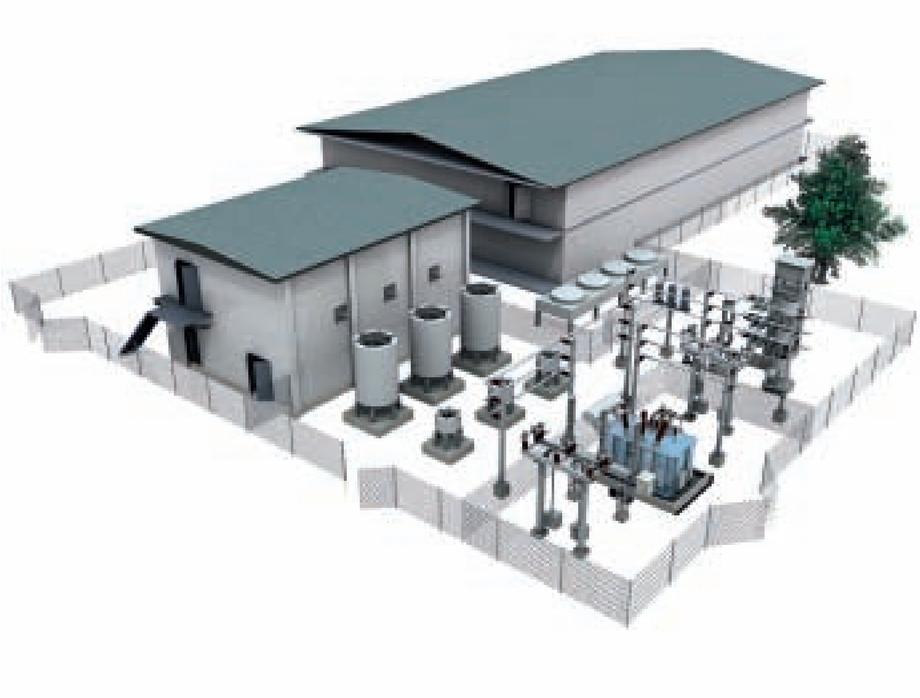


Storage for stability

The next FACTS generation

ROLF GRÜNBAUM, PER HALVARSSON – One of the challenges of a smart grid is ability to cope with intermittent and variable power sources. But this is a must, since power sources such as wind and solar are becoming increasingly important. ABB is meeting this challenge through its energy storage solutions. The newest member of the ABB FACTS family is one such solution, combining SVC Light® and the latest battery energy storage technology. This "marriage" of technologies enables the balancing of power to accommodate large amounts of renewable energy. Likewise, it can help improve stability and power quality in grids with a greater reliance on renewable generation.

1 An artist's view of an SVC Light® with Energy Storage installation. A typical rating of ±30 MVAr, 20 MW over 15 minutes will have a footprint of around 50x60 m.



As the prevalence of renewable power grows, increasing demand is being placed on maintaining grid stability and fulfilling grid codes. ABB's answer is SVC Light® with Energy Storage, a dynamic energy storage system based on Li-ion battery storage, combined with SVC Light → 1. SVC Light is ABB's STATCOM [1] concept, which is connected to the grid at transmission as well as subtransmission and distribution levels. State-of-the-art IGBTs (insulated-gate bipolar transistors) are utilized as switching devices in SVC Light.

ABB's SVC Light with Energy Storage solution is designed for industry-, distribution- and transmission-level dynamic energy storage applications, focusing on those that require the combined use of continuous reactive power control and short-time active power support. The technology enables the independent and dynamic control of active as well as reactive power in a power system. The control of reactive power enables the subsequent control of grid voltage and stability with high dynamic response. With the control of active power, new services based on dynamic energy storage are introduced.

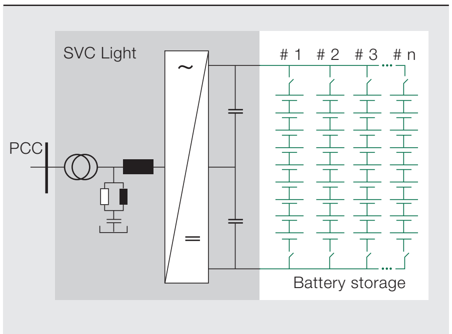
The energy storage solution can be used for load support as well as ancillary grid services, eg, regulating power frequency. Another promising use is as part of the infrastructure for PHEVs (plug-in hybrid electric vehicles). And its highly scalable ability to store energy is remarkable. At present, rated power and storage capacity are typically in the range of 20 MW; however, up to 50 MW for 60 minutes and beyond is possible with this new FACTS technology. And as the price of batteries continues to drop, applications requiring larger battery storage will become viable, enabling for example multi-hour storing of renewable power during low demand for release into the grid during higher demand.

Basic mechanisms

The energy storage system is connected to the grid through a phase reactor and a power transformer → 2. SVC Light with Energy Storage can control both reactive power *Q* as an ordinary SVC Light, as well as active power *P*. The grid voltage and the VSC (voltage source converter) current set the apparent power of the VSC, while the energy storage requirements determine the battery size. Consequently, the peak active power of the battery may be smaller than the apparent power of the VSC; for instance, 10 MW battery power for an SVC Light of ± 30 MVAr.

As a contingency typically lasts for mere fractions of a second, the required back-up power must be made available for only a short time. Similarly, an ancillary

2 Basic scheme of SVC Light with Energy Storage

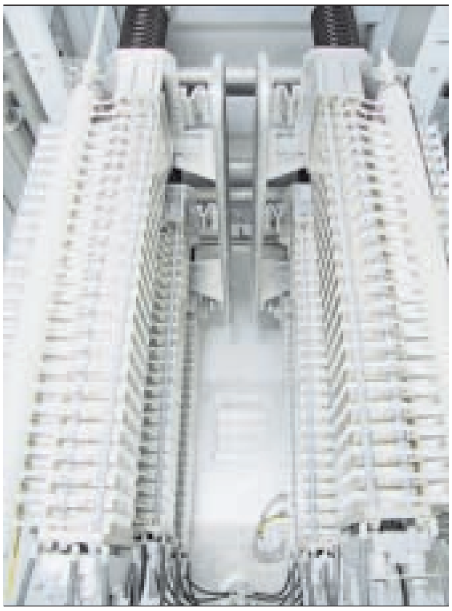


The technology enables the independent and dynamic control of active as well as reactive power in a power system.

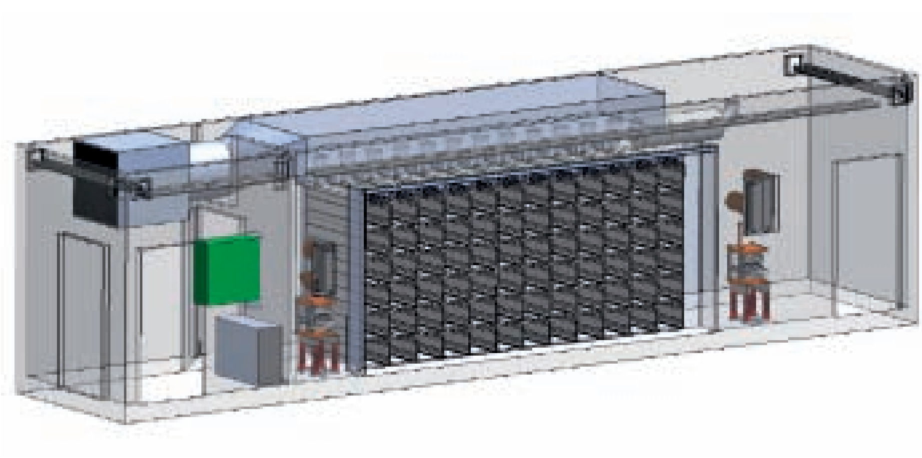
Footnote

1 STATCOM: Static synchronous compensator, a device similar in function to an SVC but based on voltage source converters.

3 VSC valve



4 Battery room



service like area frequency control will generally be needed for only a few minutes at a time. An energy storage system can then provide the necessary surplus of active power and later be recharged from the grid during normal conditions.

Main system components

A complete SVC Light with Energy Storage system is comprised of the following:
- Power transformer
- SVC Light
- Battery system
- AC and DC high-voltage equipment
- Control and protection system
- Auxiliary power equipment

The modularized design of the new energy storage technology makes it simple to scale, in power rating as well as energy. Its batteries and VSC are integrated, with detailed supervision and status checks of both within the same system. It focuses on safety and ensures the ability to respond to the consequences of possible faults. In addition, the solution boasts low losses and very high cycle efficiency.

The VSC is composed of IGBT and diode semiconductors → 3. To handle the required valve voltage, the semiconductors are connected in series. Water cooling is utilized for the VSC, resulting in a compact converter design and high current-handling capability.

Each IGBT and diode component is contained in a modular housing consisting of a number of submodules, each of which has multiple semiconductor chips (ie, ABB's StakPak™ semiconductors).

Battery system

Since SVC Light is designed for high-power applications, and series-connected IGBTs are used to adapt the voltage level, the pole-to-pole voltage is high. Therefore, a number of batteries must be connected in series to build up the required voltage level in a battery string. To obtain higher power and energy, several parallel battery strings may be added.

The battery system is made of rack-mounted Li-ion modules. An array of battery modules provides the necessary rated DC voltage as well as storage capacity for each given case. The Li-ion batteries have undergone thorough testing for the application in question [1]. A battery room is shown in → 4.

The Li-ion battery technology selected for SVC Light with Energy Storage has many valuable features:
- High-energy density
- Very short response time
- High power capability both in charge and discharge
- Excellent cycling capability
- Strongly evolving technology
- High round-trip efficiency
- High charge retention
- Maintenance-free design

Applications

Dynamic energy storage is finding uses in a multitude of areas. Not only can it support the black start of grids, it can also bridge power until emergency generation is online and provide grid support with an optimum mix of active and reactive power. This type of storage is an alternative to transmission and distribution reinforcements for peak load support, and enables optimum pricing. It becomes possible to reduce peak power to avoid high tariffs. Dynamic energy storage can also provide power quality control in conjunction with railway electrification, and help balance power in wind and solar generation, which have stochastic behavior.

ABB's dynamic energy storage system will be available in 2010.

Rolf Grünbaum
Per Halvarsson
ABB Power Systems, Grid Systems/FACTS
Västerås, Sweden
rolf.grunbaum@se.abb.com
per.halvarsson@se.abb.com

Reference

[1] Callavik, M., et al. (October 2009.) Flexible AC transmission systems with dynamic energy storage. EESAT 2009, Seattle, Washington, USA.

Smartness in control

New integrated SCADA/DMS innovations put more analysis and control functions in the hands of grid operators

MARINA OHRN, HORMOZ KAZEMZADEH – Over the last decade, the electric power industry has experienced unprecedented change. This has been fueled both by technological breakthroughs and by the restructuring of the industry itself. Restructuring has seen many utilities move from a regulated environment to a more market-oriented paradigm. At the same time, the IT systems that supported transmission and distribution operations became more robust and powerful, and have now reached the point where multiple applications can be presented on a single platform. The future grid will be largely automated, being able to apply intelligence to operate, monitor and even heal itself. This smart grid will be more flexible, more reliable and better able to serve the needs of tomorrow's world. The following article is largely US-focussed, however most of the challenges and learnings are of universal applicability.

As a long-standing industry leader and innovator in the power technology sector, ABB is at the forefront of the development of IT systems for power transmission and distribution. The 1970s saw the introduction of Supervisory Control and Data Acquisition (SCADA) and Energy Management Systems (EMS), followed by Market Management Systems in the 1980s, and Outage Management Systems and Distribution Management Systems (DMS) in the 1990s. All these solutions have been developed and enhanced over the years. A more recent direction of system development has been toward a higher degree of integration in the form of a common platform.

This platform is ABB's Network Manager™. It fully integrates the above applications and also includes ABB's Network Manager DMS – an operations management system designed to help utilities reduce operating and maintenance costs while enhancing customer service. DMS provides advanced network modeling and management, integrated switching and tagging, trouble call and outage management, crew management, and also handles the recording and presentation of events.

As the fruit of many years of research, development and ample experience, as well as close collaboration with utilities around the world, ABB is uniquely qualified to understand both the big picture and the nuts and bolts of the emerging technologies and applications necessary for today's utilities.

A brief history of SCADA and DMS

Power control traces its origin to the 1920s when ABB's predecessor companies, ASEA and BBC, supplied their first remote control systems for power plants. It was not until the 1960s, however, and the advent of computerized process control, that modern power network control systems became possible.

At that time, SCADA systems were usually designed exclusively for a single customer. They were proprietary and closed off from one another. The resulting difficulties in coordination meant networks remained vulnerable. There was thus a need for strategies that could prevent faults from developing into outages of the scale of the 1977 New York blackout.

The 1980s saw computing technology advance further. Methods were developed to model large-scale distribution networks in a standardized way. Similarly, SCADA and EMS became more sophisticated, providing transmission operators with better tools to control bulk power flows. In the business world, the 1980s were also an era of deregulation. With airline, telecommunications and natural gas industries all being liberalized, regulators and utilities both began to consider whether the same could be achieved for electric power.

Such a move would have called for entirely new types of IT systems (mostly to serve the wholesale markets), as well as enhancements to existing SCADA/EMS technology. Perhaps not coincidentally, the new generation of control systems that had emerged by the early 1990s was able to fulfill these demands.

Progress in computing also changed DMS and OMS. DMSs had originally been distribution-level extensions of SCADA/EMS systems or stand-alone systems, but the unique demands of distribution operations made them more clearly distinct.

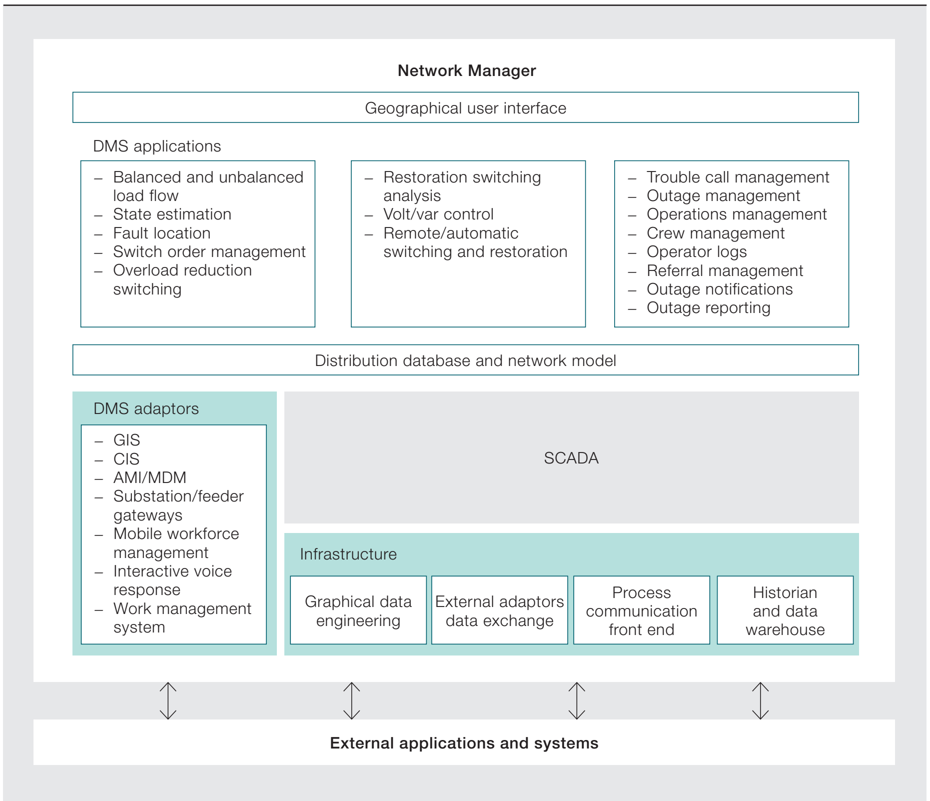
Classical monitoring and control systems for distribution networks were relatively low-tech. Typically, such a system was based on a wall board displaying the system's status. Such a board would often be covered with sticky notes and pushpins concerning ad hoc changes. This made the overall system difficult to monitor and inflexible and also presented security challenges. The distribution circuit maps used for maintenance work were paper based. They were often annotated manually and risked being out of date. The orders used to plan, execute and track scheduled switching on the system were also paper based. Outage calls from customers were received by operators who did not always have direct access to all the necessary information. These outages were also tracked with paper-based tickets. Communication with crews in the field was radio based. Crews had to inform the operating centers of their location, and the communication of switching, the placement of tags and other operations were coordinated verbally.

> As distribution systems continue to become ever "smarter" and more secure, the operations centers that control them are also changing to take on new roles in managing the evolving grids.

This should not imply that distribution operations stood still over time. As technology and business needs changed, so too did many distribution operations centers. Many SCADA systems were extended from the transmission system to cover monitoring and control of distribution-side medium-voltage (MV) feeder breakers. In some cases, the reach of SCADA was even extended out beyond the MV feeder circuit breaker to equipment such as reclosers, switches and capacitor switches.

1 The coordination of and communication with field crews is an important aspect of network management.

2 Network Manager is an integrated platform for SCADA, DMS and OMS.



Analytical software and other advanced applications are providing more far-reaching analyses and permitting automated operations.

DMS continues to evolve

As distribution systems continue to become ever “smarter” and more secure, the operations centers that control them are also changing to take on new roles in managing the evolving grids. The separate IT systems used in control centers are becoming more streamlined and are communicating seamlessly to provide an integrated monitoring and management system. Analytical software and other advanced applications are providing more far-reaching analyses and permitting automated operations. The control systems of operations centers are not only helping to make the grid smarter, but are also helping to improve support for operations, maintenance and planning. Such integrated operations centers are helping distribution organizations meet their goals despite ever-increasing demands ➔ 1.

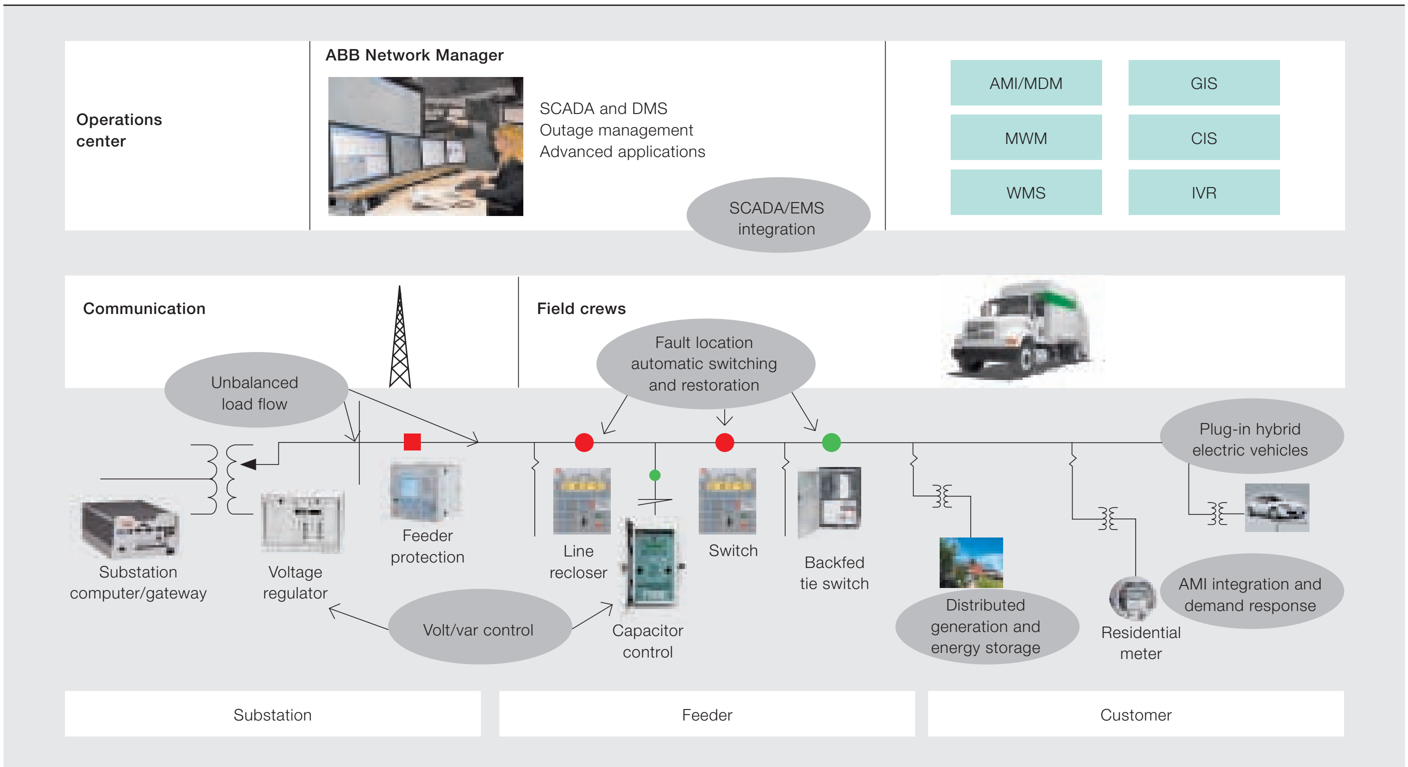
Control center systems

Within the last few years, several interconnected but external factors have accelerated the development and expansion of applications for smart grid technology. These include society, government, the changing business environment and technology.

The increasing role of renewable energy and distributed generation and the associated demand-response issues are calling for fresh approaches in grid management. Market liberalization and power trading are furthermore permitting end users to choose the source of their power. Another important contributor is the increasing cost of generation and transmission, both in terms of infrastructure and fuel. From a business perspective however, distribution organizations are also looking to smart grids to help them maintain or improve reliability, increase asset utilization, deal with aging infrastructure and help reduce the impact of knowledge loss as employees reach retirement age in many parts of the world.

Another significant enabler of the development of smart grids is technology: Many of the required tools and capabilities were simply not available some years ago. One such resource is communication. Distribution companies can now choose between many different means of communication: They can use a dedicated network they themselves own (eg, SCADA radio networks), or use third-party infrastructure (eg, cellular communications). Various factors may influence such a decision. One trend, however, is definite: The importance of two-way communication is set to increase.

The number of distribution equipment items on the feeder featuring sensing, 3 The operation center system of the future integrates various IT systems as well as field devices and customer information.



Many distribution organizations are enhancing substation automation. This improves access to information in the intelligent electronic devices.

data processing, control, and communications capabilities is increasing. Smart devices and appliances are even entering home networks. The deployment of this technology will depend upon the development and unification of interoperability standards.

The benefits of systems integration

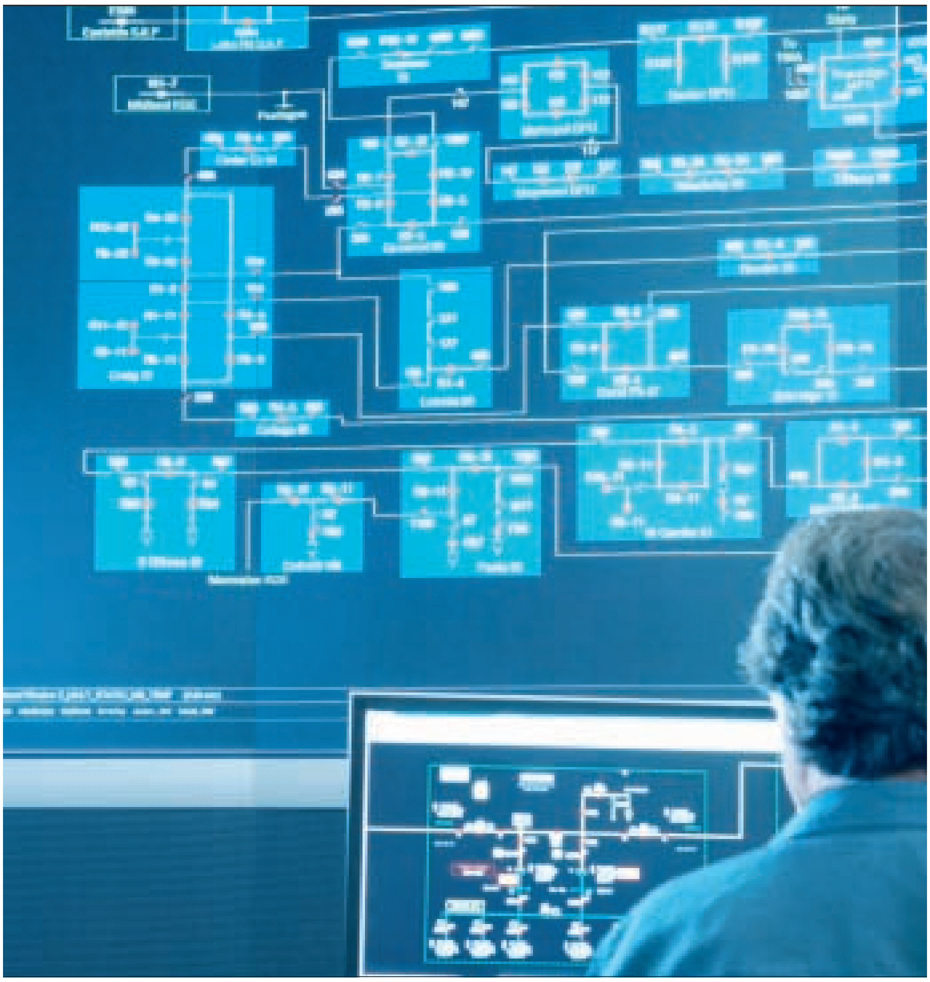
ABB is a global leader in the development of the smart grid, and has invested much time and resources in developing the operations-center systems that are a critical part of any smart grids solution. Three important areas of systems integration are DMS integration with SCADA, advance metering infrastructure (AMI) integration with DMS, and the integration of data from substation gateways and intelligent electronic devices (IEDs).

ABB has long been a leading advocate of the integration of SCADA at the distribution level with DMS applications. With more distribution companies now installing additional SCADA on the distribution system, ABB is continuing to improve the outreach of its integration solutions. Available functionality now includes the transfer of status/analog points from SCADA to the DMS; the sending of supervisory control and manual override commands from the DMS to the SCADA system; and an integrated user interface running on the same PC operator console with integrated single sign-on for users → 2.

Utility grid operators are seeing tangible benefits from implementation of integrated SCADA/DMS systems. This includes increased operator efficiency within one system, thus eliminating the need to use multiple systems with potentially different data. It also includes integrated security analysis for substation and circuit operations to check for tags in one area affecting operations in the other, and streamlined login and authority management within one system. Operators have also noted improved, consolidated system support for DMS, OMS and distribution SCADA.

Much of the discussion about developing the modern-day smart grid has, until now, revolved around the potential of AMI and emerging advanced metering technologies. As a result, installations of AMI systems are rapidly growing in number. ABB is now developing ways for distribution grid operators to improve the leverage of AMI data. Interfaces between AMI, meter data management (MDM) and SCADA/DMS have been created and improved for outage notifications, meter status queries and restoration notifications. Resulting benefits include: reduced customer outage times and a more efficient use of resources in the field. The use of other AMI data in DMS applications, such as voltage indications and interval-demand data, has also been explored. Benefits of this include better voltage profiles throughout the system and an improved understanding of system loading.

4 Advanced applications allow operators to analyze system conditions more quickly and make better operational decisions.



Additionally, many distribution organizations are enhancing substation automation and the number of substation gateways on their systems. This improves access to information in the IEDs that are installed in substations and distribution systems. The advanced communications capabilities that many of these IEDs possess include more intelligent recloser controls, switch controls, and voltage regulator controls. Integration of these systems with the DMS allows for decentralized control at the substation/feeder level, while providing system optimization through the DMS at the system level [1]. Integrating SCADA/DMS with other utility systems provides a truly integrated operations center for managing the smart grid.

The integrated operations center

A smart and fully integrated distribution operations center will include DMS applications for the management of the distribution systems with respect to efficiency, voltage control, equipment loading, work management, outage management and reliability. These DMS applications utilize a model based on the distribution database and electrical network topology. The network model uses data from a geographic information system (GIS), and is periodically updated to retain accuracy.

With more distribution companies now installing additional SCADA on the distribution system, ABB is continuing to improve the outreach of its integration solutions.

A central aspect of a smart and integrated distribution control system is the integration of the various IT systems found within it → 3. Many distribution companies are expanding the reach of SCADA beyond the distribution substations and onto the feeders, allowing for improved situational awareness and control of the distribution system. Interfaces to other systems include AMI and MDM systems, and substation/feeder gateways and data concentrators.

The strategy for sharing between the integrated operations center and field devices will differ from one distribution organization to another. There might even be several approaches used within a single utility.

Advanced network applications

With its Network Manager platform, ABB is the industry leader in the development of advanced applications for distribution system management. The Network Manager platform provides advanced applications that use the network model to provide recommendations for optimal network operation. The platform includes built-in advanced DMS applications for power flow analysis of the distribution network, optimal operation of capacitors and regulators, and fault and restoration switching analysis for faults and outages → 4.

The Network Manager Distribution Power Flow (DPF) application is an integrated application that provides unbalanced power-flow solutions for the online analysis of the real-time network, on-demand analysis of “what-if” scenarios in simulation mode, and automatic analysis of service restoration switching plans. The Network Manager DPF application is designed to accommodate large scale distribution models extracted from GIS and provide fast solutions in realtime. The application can support distribution networks connected in meshed configuration and include multiple swing sources, electrical loops and underground phase loops.

Footnote

1 See also “Information, not data“ on pages 38–44 of *ABB Review* 3/2009.

The Volt/var Optimization (VVO) application enables a distribution company to minimize peak demand and reduce real power losses. This defers the need for additional generation, transmission, and substation capacity, reduces fuel and power purchase costs, and hence reduces greenhouse emissions. The VVO application monitors the distribution network and computes the optimal distribution control settings by minimizing a weighted function of demand, loss, and voltage/current violations in three-phase, unbalanced and meshed distribution systems. The VVO application computes the optimal control settings for switchable capacitors and tap changers of voltage regulating transformers.

The Network Manager Fault Location (FL) application utilizes short-circuit analysis and can help significantly reduce CAIDI and SAIDI [2] values, by reducing the time required for troubleshooters or repair crews to locate system faults. The application computes the possible locations of faults on distribution circuits by looking at fault current measurements and real-time network connectivity.

> Demand response, whether controlled by the electricity provider or the consumer, will impact power flow and voltage profiles.

The Network Manager Restoration Switching Analysis (RSA) application provides the operator with a quick method to identify switching options to isolate a faulted area and restore power to as many customers as possible without creating new overloads. The RSA application computes and analyzes switching plans to isolate a specific fault location and restore power to customers isolated from the fault zone.
These applications provide decision support to operators in manual mode and support fully automated operation without operator intervention in automated mode. As utilities move more and more toward smart grids and utilize better data and more advanced technologies, advanced applications will increasingly be run in automated modes, further improving reliability and efficiency of distribution operations.

The future of smart distribution centers

The integrated operations center will be a key to the smart distribution grid. ABB is continuing to increase the functionality of operations centers to meet distribution organizations' technical and business requirements.

The overall operation of distribution systems is certain to become more complex. Growth of distributed generation and energy storage will affect power flow on the system. Demand response, whether controlled by the electricity provider or the consumer, will also impact power flow and voltage profiles. In addition, there is an increasing trend to deploy additional intelligence in devices on the distribution system, such as intelligent electronic devices (IEDs), substation computers and gateways, sensors, and advanced meters. Some of these will result in additional local control actions, further increasing the complexity of distribution systems' operation.

In the presence of increasing amounts of decentralized intelligence and control, the integrated operations center will be a centralized way of overseeing and coordinating the entire system.

What next?

The smart distribution grids of the 21st century will require innovative operation centers. ABB is investing heavily in the further development of integrated operations centers for smart distribution grids. This includes both the advanced integration of existing systems and the development of new applications.

Smart grid operators will have a comprehensive view of the distribution system, including system status and monitoring, control, outage response, planned work, optimal equipment loading, and improved control over distributed generation, energy storage and demand response resources. These integrated distribution operations centers will help distribution companies in their mission to meet the goals of customers, owners, employees and society itself.

Marina Ohrn
ABB Power Systems, Network Management
Zurich, Switzerland
marina.ohrn@ch.abb.com

Hormoz Kazemzadeh
ABB Power Systems, Network Management
Raleigh, NC, United States
hormoz.kazemzadeh@us.abb.com

Footnote

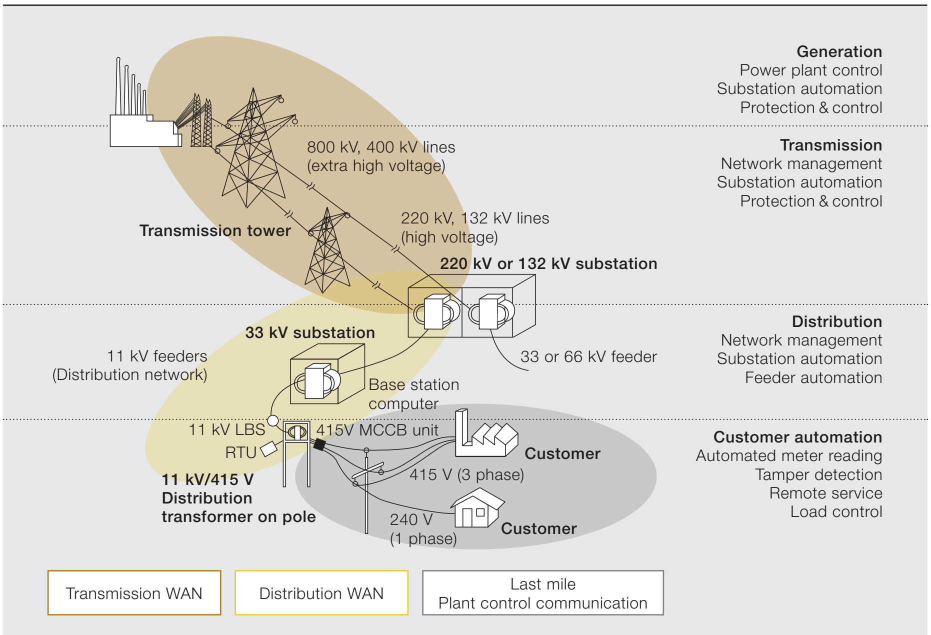
2 CAIDI: Customer Average Interruption Duration Index, calculated as the sum of all customer interruption durations divided by the number of those interruptions. SAIDI: System Average Interruption Duration Index, calculated as the sum of all customer interruption durations divided by the total number of customers served.

Connected

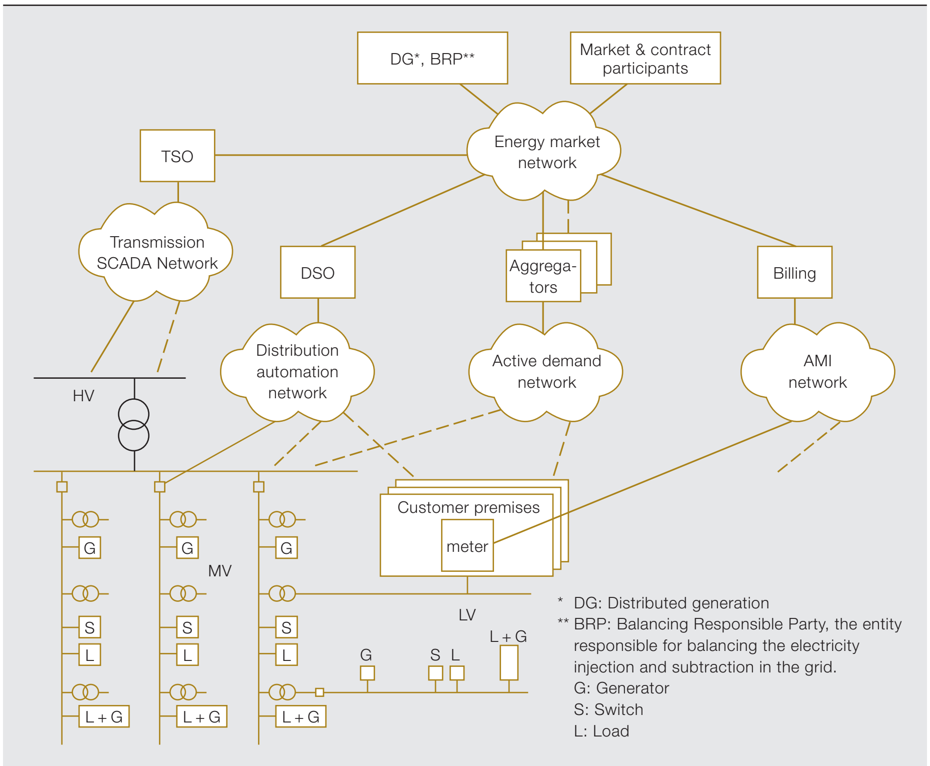
The nervous system of the smart grid

DACFEY DZUNG, THOMAS VON HOFF, JAMES STOUPIS, MATHIAS KRANICH – The evolution of smart grids, featuring more and more sophisticated control requirements, is leading to an increase in communication needs. Utility communications actually predate the launch of smart grids by many decades: In fact BBC (one of ABB's predecessor companies) commenced offering ripple control more than 60 years ago, permitting the remote operation of boilers, dryers, washing machines and other large loads during peak demand periods. As grids evolved, so did control needs and hence the demand for communication technologies. Today, power distribution networks are increasingly developing toward smart grids. Features of such grids include distributed generation, participation of the user in the liberalized market and an increased use of automation (including operational distribution automation, active demand management and automatic meter reading). The latter calls for a communication network to connect the protection and control devices used in the distribution grid. A key requirement is interoperability and reliability, ie, all control and protection devices must be able to communicate over a variety of channels.

1 Overview of utility communications



2 Communication requirements in a smart grid



A single regional area network may support all Smart Grid functions of Distribution Automation, Active Demand control, and Automatic Meter Reading.

Smart operation of the electric distribution grids began more than 60 years ago, when BBC and other companies began implementing ripple-control systems in several European countries. These permitted load peaks to be managed through the selective connection or disconnection of groups of electrical loads [1]. This ripple-control system uses the distribution line itself as a reliable communication medium. The utility sends electrical signals at audio frequency, which are able to pass through medium and low-voltage transformers and are detected by ripple-control receivers connected to low-voltage (LV) lines on the customer premises. These commands remotely switch large loads or groups of loads such as washing machines, hot water boilers, electrical heating and street lighting. The availability of a reliable communication channel between the control center and the end user's equipment thus permits utilities to better control load peaks.

ABB provides electric utilities with turnkey solutions for wide-area communication networks → 1. For SCADA (supervisory control and data acquisition) applications in the HV power transmission grid, wide-area communications links are based on broadband optical-fiber links, digital point-to-point microwave radio, and point-to-point communication using the HV power lines themselves [2]. A number of standardized protocols are in use for such applications [3].

A changing market

As discussed elsewhere in this issue of *ABB Review* [1], the economic and regulatory framework for the power grid and its operation have changed in the last decade. Power markets have been deregulated and the share of distributed power generation has increased. In a liberalized power market, consumers can be active market participants: Due to the increase in distributed power sources, power distribution no longer occurs in the traditional tree-like manner with one-way flows from large generating plants to consumers. Local production, storage, and consumption units are distributed geographically, and as a result, the direction of power flow in the distribution grid may change rapidly, requiring a higher degree of protection and control. At the same time, dependency and expectations of customers on the availability of power has risen. This is also mirrored by recently introduced or upcoming regulations that penalize utilities for outages. The objective is to maintain and increase power quality and reliability: A measure for this reliability is the System Average Interruption Frequency Index (SAIFI), which is taken as a base for compensation payments. To fulfill the rising requirements, the distribution grid requires a higher degree of smart automation – and a smart automation system requires an advanced communication infrastructure.

Communication requirements for the smart grid

Much of the emphasis of smart grids is on regional-area medium- and low-voltage distribution infrastructure. From the perspective of communications, smart grid functions can be categorized into three classes according to their communication requirements → 2:

Distribution automation (DA)

DA concerns the operational control of the grid, ie, monitoring currents and voltages in the distribution grid and issuing commands to remote units such as switches and transformers. When a fault occurs on an MV segment, protection switches should isolate it. The paths of power flow should then be rapidly reconfigured using MV switches to restore the power supply to the largest possible area. Remote reconfiguration performed by the MV distribution system operator (DSO) or substation computer is a main function of DA. Typically, several tens or hundreds of remote units must be addressable. The communication latencies for such applications are in the hundreds of milliseconds to several seconds. It is important to note that distance protection functions requiring fast communications with latencies of milliseconds are not typically supported.

> The economic and regulatory framework for the power grid and its operation have changed in the last decade.

Active demand control (AD)

AD functions perform active control and scheduling of energy demand, storage, and distributed generation, and are based on volume and price signals. The objective is to increase grid efficiency and avoid overloads through a combination of optimized scheduling/forecasting and load shedding. This functionality is less time critical as the distribution automation and the latency requirements are in the range of several minutes.

Advanced meter reading (AMR)

AMR records the actual realized power flows and calculates the appropriate billing information, taking into account any time- and contract-dependent prices. The corresponding AMR infrastructure (AMI) connects thousands to millions of meters to the billing center, some in difficult-to-reach locations. Actual cumulated energy data or load profiles for billing need be transmitted only daily or monthly.

Smart homes may be connected to the smart grid [4], and further (local-area) communication requirements may hence exist within buildings [5]. The present article, however, addresses only the regional-area communications needs of smart grids. [2]

The above analysis shows that the technical requirements on communications for the smart grid are moderate, in particular regarding data rate and latencies (protection functions being excluded). Where some communication delays are acceptable, high communication reliability can be assured by error detection and automatic retransmission. The main selection criteria are thus the costs of procuring and installing equipment and the operation life-cycle costs.

Communication technologies for the smart grid

A wide range of communication technologies are currently available to support smart grid applications. These range from wired products to wireless devices and include hybrid systems incorporating both wired and wireless technologies. It is unlikely that one technology alone will ever provide a complete solution for all smart grid communications. Interoperability of different technologies will thus be a key requirement: Devices on different networks using different communication media must be able to communicate with each other. Interoperability also refers to equipment from different manufacturers and subsuppliers, hence technical standards play a key role.

In order to select a communication system for smart grid applications, many issues must be considered, some of which are listed in → 3.

The technologies that will be deployed for smart grid applications will depend on these criteria and the requirements of each utility company. The main technical criteria are communication performance, security and interoperability. The bandwidth supplied by the communication infrastructure must be scalable and capable of supporting the thousands to millions of data points that exist in a utility system. Due to regulatory and operational requirements regarding cyber security of critical infrastructures, security is also increasingly becoming a major factor.

Interoperability and standardization are thus central attributes of future technology. They will reduce the utility's engineering time, with "plug and play" type applications becoming more prevalent. Only

3 Criteria to be considered when selecting communication media

- Availability of communication media, such as existing copper- or fiber-optic connections
- Availability of wire ducts, or sites for radio transmission towers
- Communication performance, such as data rate (bandwidth) and transmission latency for a given number of communication nodes
- Communication reliability and availability
- Security requirements, ie, confidentiality, integrity, authentication
- Interoperability and application of standards
- Upfront investment
- Recurring costs, eg, operational costs such as monthly data transmission fees
- Future-proof technology with respect to changes in technology

Footnote

1 See for example "The next level of evolution" on pages 10–15 of this edition of *ABB Review*.

systems fully satisfying these criteria will be capable of supporting the DA, AD, and AMR/AMI applications of a smart grid.

The major communication technologies that are currently available in the market to support smart grid applications are the following → 7:

Wired utility communication networks
A utility may build ducts to its power-distribution nodes to carry communication wires alongside the power cables. These wires may be copper wires, carrying low-rate telephone modem signals or broadband digital subscribe line (DSL) signals. Newer systems will be optical-fiber based, and carry, eg, Ethernet signals to establish large broadband metropolitan area networks (MANs) with user data rates of many Mb/s.

Utility-operated radio systems
Such networks → 4 are erected and operated by the utility. Radios typically offer narrowband communications with user data rates of only several kb/s, but have a long range (up to 30 km). Radio frequencies are either in the free unlicensed bands ("Ethernet radios" using spread-spectrum transmission at 900 MHz in North America), or in bands requiring license fees (narrowband radio modems at VHF 150 MHz or UHF 400 MHz in Europe [6]). For automatic meter reading, specialized radio systems with low-power transmitters and drive-by readers have been deployed. For high data rates, utility point-to-multipoint microwave systems are available.

Public cellular data systems
Established and ubiquitous examples of this type of network are CDMA [2], and GSM/GPRS [3] → 4. New fourth-generation systems being introduced are WiMax and the Long-Term Evolution (LTE) of UMTS. Such systems are optimized for public consumer usage in terms of coverage and traffic load, so it must be assured that performance is sufficient in terms of range for mission-critical grid control. In addition, adopting these technologies means utilities must enter into service agreements with third-party cellular service providers, implying recurring operating costs.

Satellite communications
Both low- and high-data rate systems are available, the latter typically requiring more costly parabolic antennas. Satellite communication systems are also third-party operated. In regards to bandwidth allocation satellite providers offer shared as well as dedicated services. For DA as well as AD applications dedicated services are normally used whereas for AMR shared services are sufficient.

Power and distribution line communication (PLC, DLC)
An obvious communication medium for electric utilities is the power distribution network itself → 5. On the HV grid, HV-PLC is a well established technology [6]. On the LV network, many attempts have been made to provide broadband over power line (BPL) service to consumers as an Internet-access technology. Aggregate data rates of up to tens of Mb/s are possible under good network conditions, but communication distance and availability may be insufficient for smart grid applications due to range and reliability being more critical than high data rates. Technologies and standards for narrow-band DLC on the MV and LV grids are currently being developed.

4 Wireless communications: technologies and applications

Technology	Standards	Operator / owner	Frequency band	Data rate	Applications
VHF/UHF radio	Proprietary, PMR	Utility	150 MHz / 400 MHz	Narrowband	Voice; DA, SCADA
2.4 GHz wireless	WLAN, ZigBee	Customer, utility	2.4 GHz	Broadband	(Short range) AMR, Home Automation
Point-to-multipoint	Proprietary, WiMAX	Utility or 3rd party	5–60 GHz	Broadband	High speed data; DA, SCADA
Public cellular data services	GSM/GPRS UMTS CDMA	3rd party	900/1800 MHz (EU) 800/1900 MHz (US)	Narrowband / broadband	Voice, data; DA, AMR
Satellite communication	Proprietary	3rd party	6 GHz, 12 GHz	Narrowband	AMR

5 Power line and distribution line communications: classification and applications

	Narrowband powerline communication	Broadband powerline communication
High-Voltage power transmission lines	Long-distance SCADA communications [6]	–
Medium-Voltage power distribution lines	Distribution Automation Active Demand	Backbone communication network
Low-Voltage utility power distribution lines	Distribution Automation, Active Demand, Automatic Meter Reading	Public last-mile Internet access
Low-Voltage in-house power distribution lines	Home and Building Automation [7]	In-house local area network

Typically, a given smart grid operated by a utility will use combinations of these technologies and systems.

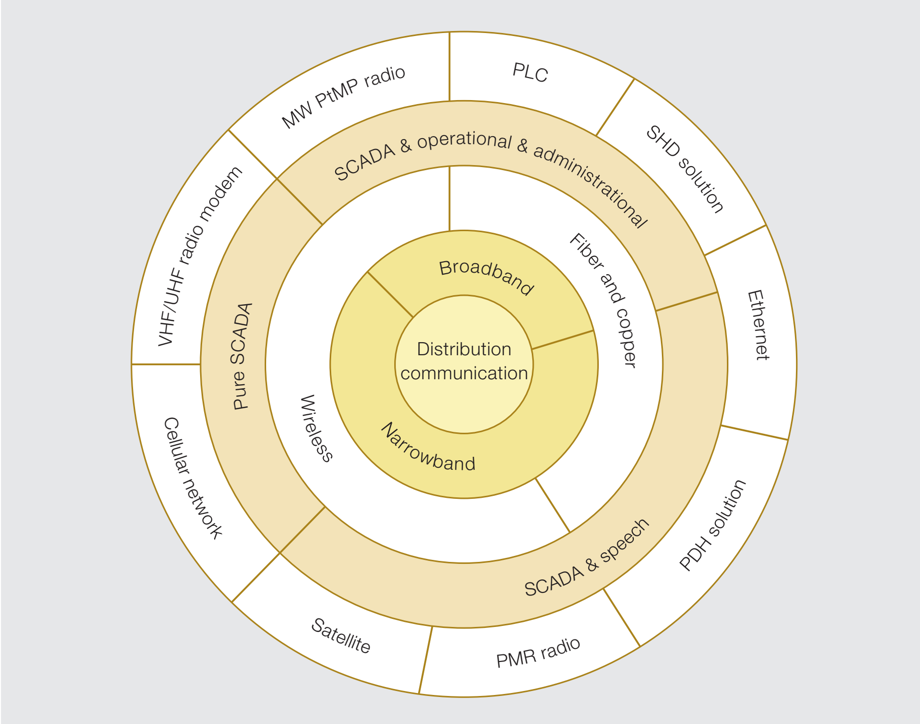
Mapping technologies to requirements
Depending on the smart grid functions, different technologies may be applicable. As described, bandwidth requirements are generally moderate, but availability must be high. Therefore utilities tend to prefer their own utility-operated infrastructures to those of third-party service providers. → 4 lists wireless systems for both of these options. In practice, utility-operated radio modems are often more suitable. As the bandwidth demand is low, radio modems are the solution with the best cost-benefit ratio. On the other hand, relying on public cellular networks allows simple and cost-efficient implementation of communications.

Deployment of new communication networks for electric utilities is easiest either using wireless, or using communication

Footnotes
2 In the United States
3 In most of the world (including the United States)

6 ABB UHF radio AR400

7 Communication options for distributed communication for the smart grid



Where some communication delays are acceptable, high communication reliability can be assured by error detection and automatic retransmission.

on the electrical power distribution grid itself. The latter, distribution line carrier (DLC) technology, has already been adopted for ripple control systems; extensive digital systems, mainly for automatic meter reading, are also in operation Factbox → 3. More reliable and flexible DLC systems providing the option to incrementally add further services are required for operating smart grids. The challenge lies in meeting higher communication reliability and range requirements as well as allowing easy deployment.

What does ABB offer?

Communication networks for smart grids are complex and may involve many different systems and technologies. ABB has the experience to support utilities in their evaluation of communication technologies. With its understanding of the utility requirements and constraints, ABB can offer long-term solutions, which will be able to satisfy future requirements. Examples for new solutions are the new ABB radio AR → 6, integration of communication modules into application devices (eg, Ethernet boards in to RTU560 family), and partnership with service providers (eg, satellite solutions). Integrated network management and routing over a variety of communication media will be supported.

Given its total offering of SCADA network management systems, RTU solutions, distribution and feeder automation products, and communication systems, ABB is an ideal partner and supplier for smart grids.

Dacfey Dzung
Thomas von Hoff
ABB Corporate Research
Baden-Dättwil, Switzerland
dacfey.dzung@ch.abb.com
thomas.von.hoff@ch.abb.com

James Stoupis
ABB Corporate Research
Raleigh, NC, United States
james.stoupis@us.abb.com

Mathias Kranich
ABB Power Systems
Baden, Switzerland
mathias.kranich@ch.abb.com

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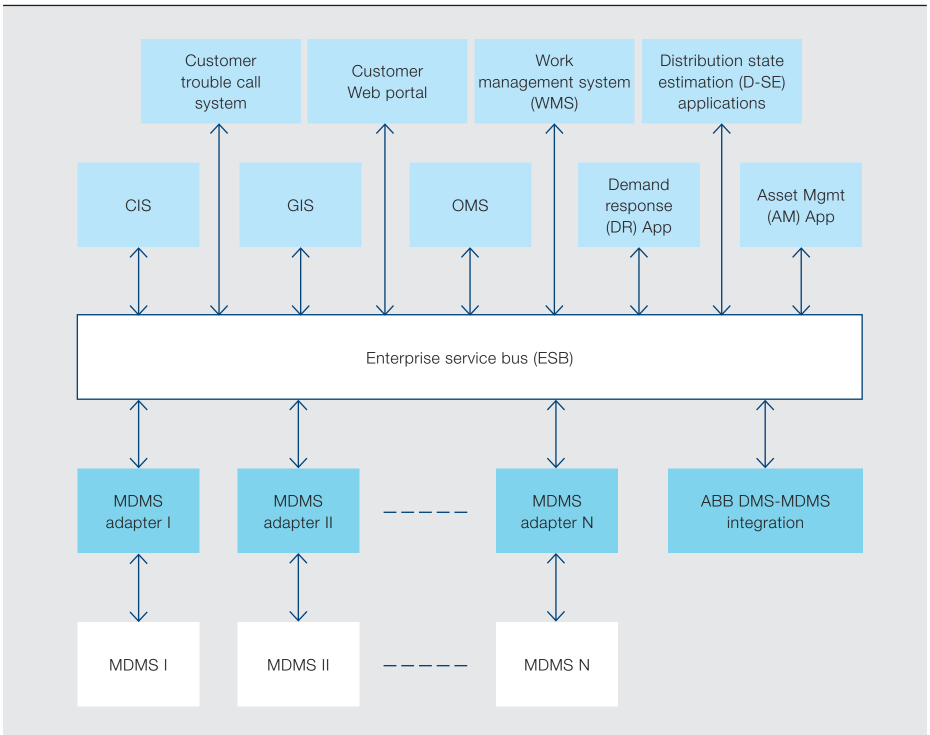
Closing the loop

Smart distribution management systems are helping to provide more efficient and reliable services

WILLIAM PETERSON, XIAOMING FENG, ZHENYUAN WANG, SALMAN MOHAGHEGHI, ELIZABETH KIELCZEWSKI – Utilities are always looking for ways of improving customer service while optimizing overall performance and reducing operating costs. At the distribution control center level, smart distribution management system (DMS) applications have the potential to help utilities achieve this by providing fast, accurate and detailed information about a distribution system so that strategic decisions can be made. Historically, the main DMS application data sources were SCADA telemetry, end-customer calls and maintenance/repair crew reports. With the industry drive toward smart grids, these sources are being augmented by a multitude of sensors with communication capabilities that are deployed for substation automation, distribution automation, and advanced metering infrastructure. Integrating these sensor data into DMS-advanced applications is essential to reaping the potential investment benefits as well as justifying the cost of creating the sensing and communication infrastructure. Through advanced applications, the distribution system provides more efficient and reliable services to customers and, at the same time, helps reduce the ecological footprint of energy production. The availability of real-time and near real-time system information not only enhances the capabilities of existing applications like outage analysis, but also enables advanced smart grid applications that were not possible before.

1 ABB's AMI-enabled smart distribution management system vision



An advanced metering infrastructure (AMI) refers to the information technology and infrastructure that collects, communicates, aggregates and disseminates the power usage, quality and status information from so-called smart meters.[1] A smart meter is not simply a point of instrumentation, but also a point of interaction (POI), or in other words, an intelligent node in the smart grid.

With the rapid deployment of AMI in many utilities, distribution management system (DMS) applications are undergoing significant renovation so that they can make faster and smarter decisions, and achieve network control objectives quicker with less cost and greater reliability. DMS/AMI integration is not without its challenges but smart grid applications, such as outage management systems (OMS), distribution state estimation (D-SE) and demand response (DR) among others, set to benefit from this integration, the utilities will have more efficient operation and customers will have more reliable power.

The benefits of energy-consumption monitoring and control

Advanced DMS applications require real-time or near real-time network information, including network connectivity (switching device on/off status), loading levels (current) at service points (load transformers at end-customer premises) and feeder sources (distribution substation transformers), as well as feeder voltage profiles (voltages along the feeder main and laterals). Conventional supervisory control and data acquisition (SCADA) telemetry can provide information about substation and feeder equipment, but the cost of the infrastructure needed to gather information at the load transformer level and beyond is simply too prohibitive. This can be overcome by using an existing AMI, which not only provides load transformer information at a much lower cost – only the DMS/AMI integration cost is incurred – but is also capable of reaching individual households.

System architecture

The integration of smart meter data into a DMS will enable a whole new breed of smart grid applications at the control center level. However, the standardization of this integration is not easy because of the many types of AMI technologies that exist and the varying requirements for each smart grid application. ABB is pursuing a vision that the meter data management system (MDMS) from any AMI vendor can be easily integrated with ABB Network Manager DMS products. The core of this vision is shown in → 1 where the MDMS adapters enable the transfer of AMI data from any vendor's MDMS via ABB's smart DMS enterprise service bus (ESB).

Advanced outage management

An outage is a sustained interruption of power and occurs when a fuse, recloser or circuit breaker has cleared a fault and, as a result, customers located downstream of the protective device lose power. During such a power outage and without direct communication between the customer's meter and the DMS, the most sensible and perhaps only approach is for the customer to call the local utility company to report the outage and then wait until power is restored. With AMI, this action is totally unnecessary because the outage event will be automatically reported to the DMS within a matter of seconds. An outage analysis (OA) program will then continuously process the incoming outage event messages to determine exactly where power has been lost and infer the most likely location of the fault(s) before informing customers of the estimated time to restoration. AMI literally reduces the time needed for fault analysis from hours to minutes, and most importantly, it shortens the outage duration for customers.

When an outage occurs in the distribution network, an OMS, which typically has two key components: outage notifi-

Footnote

1 A smart meter can be described as a digital incarnation of the traditional electro-mechanical electric meter.

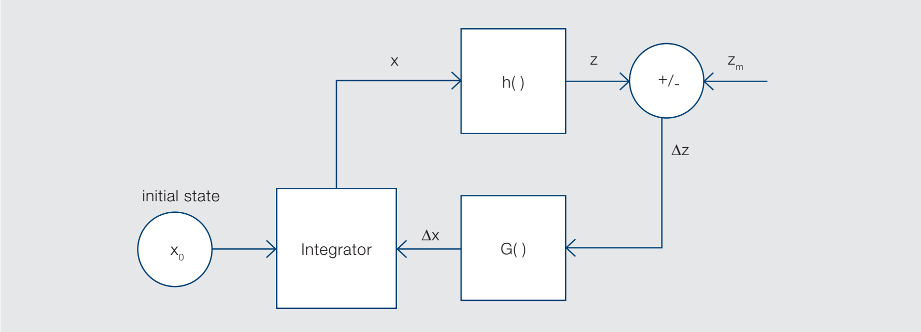
cation and restoration notification[2] – has to quickly and accurately identify the location of the outage so that crews can be dispatched to repair the damage and customers informed about the expected repair time. Two mechanisms normally used are SCADA telemetry or an outage inference engine. Historically, SCADA telemetry has been the fastest and most accurate method of identifying or verifying the location of an outage. However, due to the high cost of the communication and telemetry infrastructure, it is used as little as possible. Instead, an outage inference engine is the most applicable mechanism.

An outage inference engine automatically collects and analyzes outage calls to determine their spatial and temporal pattern, and uses the location of customer transformers and protection devices, and network connectivity to infer which protection device may have reacted. The effectiveness of this process depends on the availability and speed at which customers call to report an outage. For whatever reason, many customers either do not call or delay calling, and this in turn limits the information available to the engine and reduces the quality and confidence of the inference results.

To compensate for this, the outage inference engine introduces tunable parameters that determine the number of calls required to infer the cause of an outage event and the speed at which the system rolls up the outage to the next electrically connected protective device, ie, the system automatically groups several calls into an outage at a higher level of the electrical network. One such parameter is called the outage freeze time, which is defined as the time an outage must stay at a device before it is allowed to roll up. While a small freeze time is naturally desirable in order to identify multiple faults, the variations in call behavior often mean this parameter may be as large as 6 to 10 minutes to allow for the accumulation of the appropriate number of calls.

This is where AMI comes to the rescue – by treating AMI data as customer calls or in other words by creating an automated call system, the freeze time can be significantly reduced, thereby enabling the outage inference engine to quickly resolve multiple outages in a circuit.

2 State estimation block diagram



In addition, utilizing and incorporating the data available from smart meters can also help with the following OMS functions:
- Verification of outages
- Identification of multiple outages in the same circuit
- Identification of broken conductors
- Restoration confirmation

One of the most straightforward applications of AMI would be the verification of outages using metering data in a manner similar to SCADA data. In this case, an outage could be traced to a device if the customers downstream of the device are out of service while those immediately upstream are in service. Another application is in cases where the outage is caused by a broken conductor. The area in or around the broken conductor can be narrowed to one bounded by the customers who are out of service and those who are in service.

Functions such as distribution state estimation will benefit from the integration of smart meter and sensor data into DMS.

Finally, the DMS system can communicate with the meter to confirm power restoration. Typically, this is accomplished using automated telephone callbacks to customers. Confirmation of service by the metering network would eliminate the need to call back to confirm service.

Another function that benefits from the integration of smart meter and sensor data into DMS is distribution state estimation (D-SE).

Distribution state estimation (D-SE)

A state is defined as a set of information that uniquely characterizes a system's operating condition, and all the major functions of system operation (ie, protection, control, and optimization) require knowledge of the state of the system. D-SE uses statistical analysis and optimization techniques to derive the best estimate of the state of the system from all available measurements (observations). From this estimate, D-SE produces a real-time model that best represents the operating state of the system, which then allows engineers to see if any circuits in the system are overloaded.

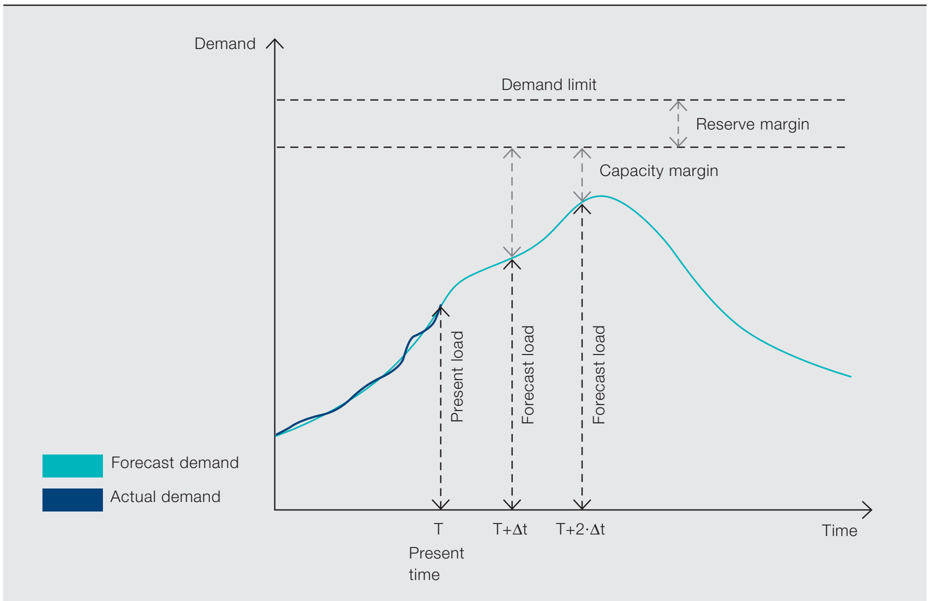
Multiple choices of an information set are possible. For example, if only the static behavior of an electric power system is of interest, a set composed of complex voltages at every node in the system uniquely determines the operating state of the system under consideration. Knowing the complex voltages at every node as well as the component model for transformers and distribution lines allows the current and power flows between any two adjacent nodes in the system to be calculated. However, for many engineering systems, directly measuring the state of the system is not possible (or practical) because only indirect measurements[3] are available. These measurements are used in state

Footnotes

2 Both these functions require distributed measurement points at customer sites.

3 Indirect measurements are functionally dependent on the state variables and therefore provide indirect information about the state of the system.

3 Estimation of the capacity margin



AMI data is valuable in helping grid operators improve the reliability and efficiency of the grid.

estimation to infer, as accurately as possible, the state of the system.

In theory, the estimation of a system state consisting of N variables needs only N independent measurements. In practice, however, a certain degree of redundancy is required to counteract the inevitable random errors in the measurements. The measurement redundancy is the ratio of the number of independent measurements to the number of state variables. Of course, the higher the measurement redundancy, the better the quality of state estimation; a redundancy value of one indicates that there are just about enough measurements to estimate the state.

Typically, state estimation is formulated as an optimization problem in which the decision variables are the state variables, and the objective function to be minimized is a measure of the deviation of the measurement function from the actual measurement. This process is illustrated in ➔ 2. In the diagram:
- x represents the state estimate
- $h(\,)$ is the measurement function
- The discrepancy, Δz, between the measurement function at the estimated state, z, and the actual measurement, z_m is used to generate a correction, Δx, using a gain function $G(\,)$.

Traditionally, state estimation has not been a viable technology for distribution networks for two reasons:
- Very few real-time measurements are available. For a distribution circuit with several thousand nodes, only a couple of measurements, usually near the head of the feeder, are available.
- Complex modeling of multiphase unbalanced distribution networks poses a big challenge to the development of efficient and robust estimation algorithms that can use different types of measurements.

The integration of meter data helps overcome these drawbacks mainly because it is capable of providing a huge amount of near real-time measurements (including power, voltage and current) at every service connection point. The availability of such information drastically improves the quality of state estimation. With a more accurate real-time system model, other DMS functions, such as voltage and var optimization, service restoration, load balancing and system configuration optimization can be performed more reliably.

Demand response (DR)

Electrical demand response (DR) refers to the short-term changes in electrical consumption by end customers in response to changes in the price of electricity over time or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [1]. From a utility perspective, peak shaving [4] is the main objective of DR although peripheral objectives, such as managing the ancillary services and improving the reliability of the overall system, can also be defined. In addition to the environmental impact of reducing electricity consumption, implementing DR:
- Helps utilities save money by postponing the expansion of the distribution system
- Provides financial benefits to customers
- Makes the overall electricity market less volatile in spot prices (ie, prices for immediate payment and delivery)

DR is often initiated at the utility where data, based on a forecasted demand, is used to estimate the capacity margin for future time intervals ➔ 3. A decrease in this capacity margin or a negative margin would cause the utility to trigger a DR event. Various DR programs offered by utilities can be customized to fit varying needs. These programs can be broadly classified into three categories:
- Rate-based (also referred to as price-responsive) programs where customers reduce their demands

Footnotes

4 Peak shaving describes the slow shedding of loads during traditional peak energy-consumption periods in case of overload.

according to the price signals they receive in advance. Prices can be updated monthly, daily or in real time. Examples of such programs are real-time pricing (RTP), critical peak pricing (CPP) and time-of-use (TOU).
- Reliability-based (also referred to as incentive-based) programs in which customers, having enrolled in any of these programs, agree to curtail demand when notified by the utility. In exchange for compliance, the customer is rewarded by receiving incentive payments, bill credits or preferred rates. On the other hand a failure to comply might lead to penalties. Example programs are direct load control (DLC), interruptible load and emergency demand response.
- Bidding programs come into play when the utility predicts a supply shortage. The utility issues a DR event and opens a bidding window, allowing customers to place bids to either curtail their demand or sell energy back to the utility in exchange for payment.

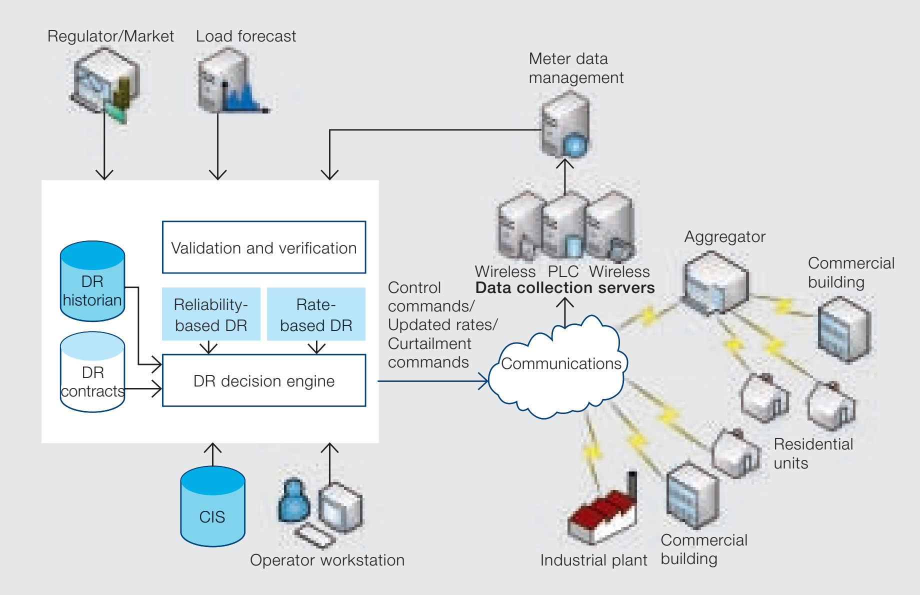
DR infrastructure

DR infrastructure combines a system-level decision-making engine located at the utility with automated and semi-automated solutions available at customer sites. The utility may communicate directly with residential/commercial/industrial end-users or indirectly through DR service providers (ie, aggregators), who assume the responsibility of regulating groups of end-customers and transmitting their aggregate impact as one load point to the utility → 4.

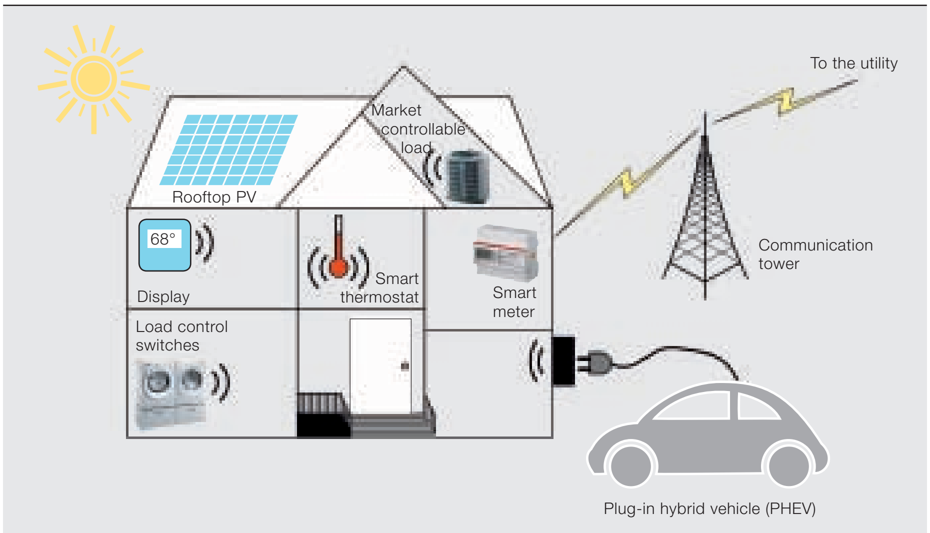
The DR engine communicates with the customer information system (CIS) in order to obtain the details of customer contracts and other related data. The terms and conditions of these contracts detail the constraints of each customer or group of customers regarding participation in a DR event. Constraints, such as the minimum notification time required; the maximum allowable number of interruptions in a day, week or season; the maximum allowable reduction; and the maximum allowable event duration determine which customers can be contacted during a certain DR event.

The DR engine also receives metering data from the meter MDMS. When applicable, it may also receive data from the SCADA system.

4 A demand response (DR) infrastructure



5 Example of a residential customer network



DR Efficiency

The efficiency of a DR program depends on the accuracy of the telemetry system used to measure and validate customer responses to a DR event. In the absence of accurate two-way metering systems, the utility relies heavily on a combination of bulk measurements available from the main substations in the network and stochastic methods, such as load allocation and statistical estimation. However, with the introduction of AMI, the prospect of accurate two-way metering is becoming more realistic. Precise real-time DR events (also known as precision-dispatched demand response PDDR) [2] allow for refined granularity down to individual customers, faster response times and higher visibility to the system operator.

AMI provides real-time two-way communication beyond the smart meter and into the intelligent devices in the house through a home area network (HAN) → 5. This way, HAN-based devices, such as smart thermostats, displays, market controllable loads and load-control switches, are linked to the smart meters and thereby to the utility and can receive data (eg, updated prices for intelligent processors) and commands, such as curtailment signals for intelligent actuators.

The integration of meter data with DR enables the adoption of real-time and near real-time programs, which in turn leads to faster response times, more accurate control, and hence improved reliability benefits for customers and the grid.

In the absence of real-time or near real-time communication between the utility and the customers, the responses of the customers to a DR event cannot be verified immediately. In such cases, the operator has to wait until the next data-collection cycle, which can occur anytime between a few hours and a few days, to process the financial calculations. For the utility, the added value of real-time or near real-time communication is the ability to verify and validate customer responses to a DR event and the DR signals generated, and take remedial action, such as contacting a second group of customers or issuing an emergency DR event, if necessary.

Smart energy management applications

Distribution systems servicing millions of commercial and residential buildings equipped with smart meters mean the volume of data to be processed will drastically increase. The challenge of managing large volumes of real-time data is amply illustrated by the August 2003 power blackout in North America in which, as Congressional hearings uncovered, no manager had a global view of that event-driven situation.

To effectively manage increased volumes of data received from meters and sensors, data management applications must be able to unify data from disparate sources, and synchronize and aggregate it into actionable information. For these purposes, AMI deployment may benefit from complex event processing (CEP) technology. CEP systems process multiple events on a continuous basis in order to identify unique events, such as an impending overload or destabilization of the grid. Data are evaluated locally and propagation is carried out only if network-wide usage is necessary.

Information visualization tools also take advantage of AMI data. These tools leverage spatial information from geographic information systems (GIS) and apply numerous modern techniques, such as color contouring, information dashboards and animation. These techniques, together with the capabilities of the outage inference engine, provide control room operators with effective tools to visually analyze the outage situation.

The graphical representation of meter readings and the ability to ping selected meters may be integrated with GIS-enabled crew management systems to make the dispatchers work more efficiently. Moreover, the operators can replay any changes of meter data throughout a time interval that facilities the detection of trends in temporal and spatial dynamics. By adding weather and temperature data to the graphical analysis, causal factors become evident and scenarios can be studied to assess any future impact.

Aggregating tools, which roll up meter data to the transformer level, are useful for highlighting areas where transformers are at risk of being overloaded and areas with a high density of under-utilized transformers (contour maps). These features may also help during emergency load shedding events to prevent an overload of the system. Generally, in most emergency situations the availability of AMI and sensor data creates opportunities for quicker damage assessment. However, additional possibilities emerge when these data are combined with terrain mapping, video and light detection and ranging (LIDAR) technologies. These technologies are already used in pole/line asset surveys and vegetation control, but still need to be integrated into the infrastructure and global data analysis.

Advancing the future

Until about 20 years ago, distribution system automation was not an urgent priority. However, continuously increasing demands for electrical energy combined with concerns over sustainability and environmental issues have lead to a global drive toward the increased instrumentation and control of distribution systems. Substation automation, feeder automation and AMI systems are being deployed at an accelerating rate throughout the world and make a wealth of data available to control systems. Even though integrating a vast amount of real-time measurements is challenging, it provides opportunities to implement new applications that help reduce service interruption duration (outage management), optimize energy efficiency (voltage and var optimization), increase situational awareness (state estimation) and engage consumer participation (demand response). ABB's research and development laboratories are taking advantage of these new opportunities to create applications enabling better grid efficiency and reliability, and better utility asset usage.

Integrating a vast amount of real-time measurements is challenging but it provides opportunities to implement new applications that improve grid efficiency and reliability.

William Peterson
Xiaoming Feng
Zhenyuan Wang
Salman Mohagheghi
Elizabeth Kielczewski
ABB Corporate Research
Raleigh, NC, United States
william.peterson@us.abb.com
xiaoming.feng@us.abb.com
zhenyuan.wang@us.abb.com
salman.mohagheghi@us.abb.com
elizabeth.kielczewski@us.abb.com

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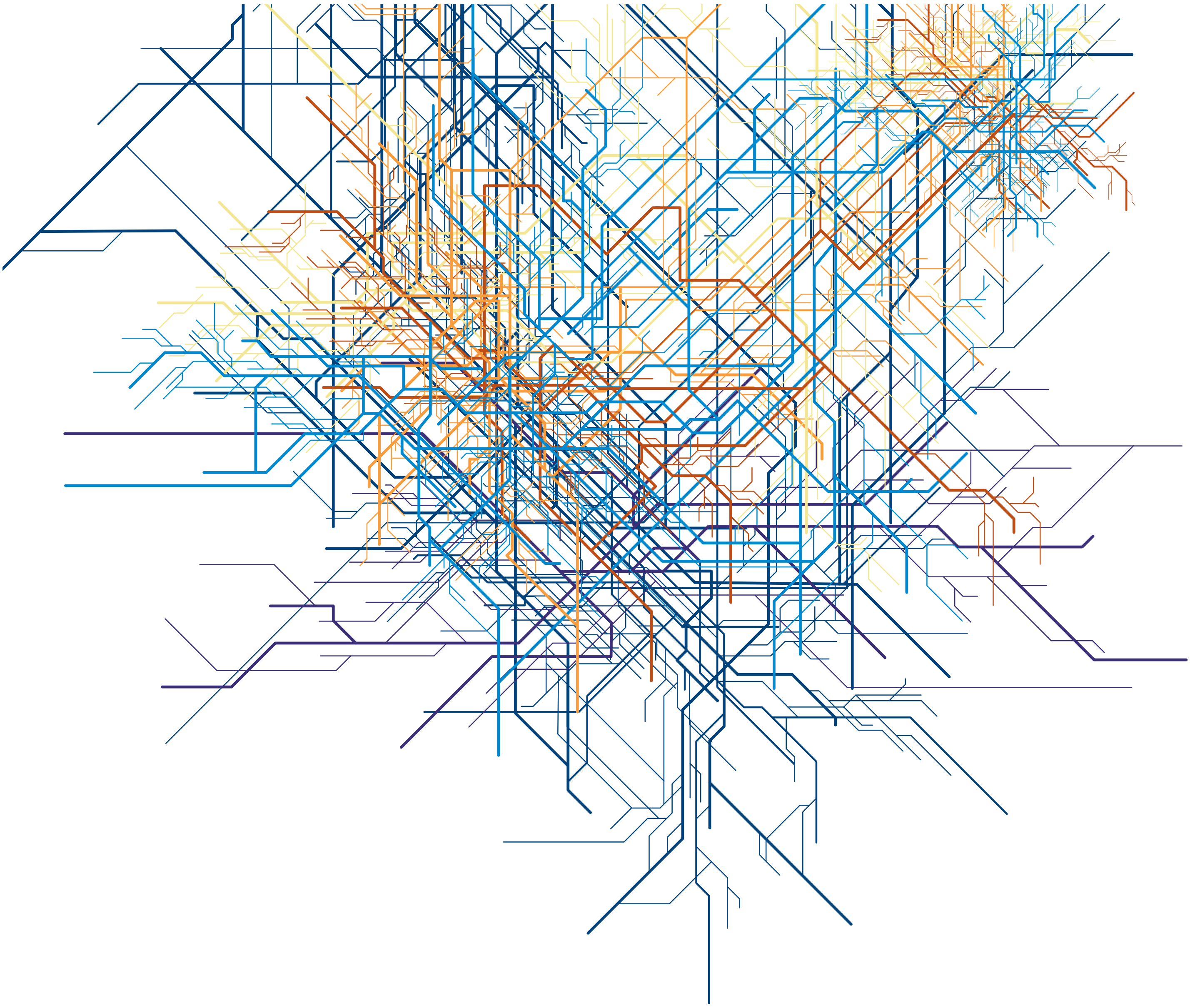


Smart teamwork

Collaborations with recognized research institutes are helping ABB meet the challenges of the future electric grid

CHERRY YUEN, ALEXANDER OUDALOV, ANDREW D. PAICE, KLAUS VON SENGBUSCH – The battle against climate change combined with the search for energy and process efficiency has been slowly but surely pushing the topic of smart grids up the agendas of many companies. In fact, since European and US governments identified them as key to meeting their environmental goals and achieving energy security, it has found its way into the popular media. While it may seem like a new concept to many, ABB has actually been active in this area for several years, developing the technologies and standards that will be needed in the future. In fact many are already being used to enable modern grid operation and provide greater efficiency, reliability and intelligence. Research efforts on smart power transmission and distribution have focused on implementing smart functionalities into both ABB products and customer installations. Some of the current efforts, carried out in collaboration with external partners and partly funded by public bodies such as the European Commission, are described in this article.

The traditional power grid is based on large centralized power stations that supply end-users via transmission and distribution systems where power flows from the top down. However, today's conflicting demands for more reliable, higher-volume power supplies from cleaner and more renewable energy sources mean this very same infrastructure must operate in ways for which it was not originally intended. The solution lies in gradually transforming the old system into a more intelligent, more effective and environmentally sensitive network that can receive power of all qualities from all sources – both centralized and distributed – and deliver reliable supplies, on demand, to consumers of all kinds. In other words, what is needed is a smart grid.

The term smart grid can mean many different things to different people. However, in ABB's view a smart grid is an infrastructure that puts the emphasis firmly on active rather than passive control. ABB's vision for the smart grid is of a self monitoring system based on industry-wide standards that crosses international borders and participates in wholesale energy trading, and provides a stable, secure, efficient and environmentally sustainable network.

There has been a great deal of discussion in the media about smart grids. In October 2009, President Barack Obama promised $3.4 billion to fund "a broad range of technologies that will spur the nation's transition to a smarter, stronger, more efficient and reliable electric system" [1]. In Europe the European Commission has been financing projects to develop the technologies that "play a key role in transforming the conventional electricity transmission and distribution grid into a unified and interactive energy service network using common European planning and operation methods and systems" [2].

While true smart grids are still a vision of the future, the technologies and standards that will be needed have been under development at ABB for some years and many are already in use. In particular, projects have been ongoing to develop an alternative approach to the transport of energy based on centralized power generation. In other words, instead of relying solely on large power plants, small generators could be used to serve villages or towns or even factories. Known as active distribution grids, they would ensure uninterrupted power to the critical communications infrastructure and control systems that drive today's economy. In addition, because the energy is created close to where it would be used the energy lost in electric transmission and distribution would be reduced significantly. ABB has been working in this area in close collaboration with external partners and their efforts have led to the execution of several demonstration projects, four of which (More Microgrids, AuRA NMS, ADDRESS and MEREGIO) are briefly discussed in this article ➔ 1.

Microgrids

Microgrids comprise medium- and/or low-voltage distribution systems with distributed energy sources, storage devices and controllable loads. They can operate when connected to the main power network or when isolated – or islanded – in a controlled and coordinated way. The microgrid concept is a logical evolution of simple distribution networks and can accommodate a high density of various distributed generation sources such as microturbines, fuel cells, solar photovoltaic systems, and small diesel, wind, hydro and energy storage devices such as batteries. Microgrids can offer supply reliability, power quality improvement, and a greener and (possibly) cheaper energy supply to energy consumers. Network operators and utilities benefit because microgrids are better able to integrate distributed generation as well as reduce losses.

Nevertheless, the technical challenges associated with the integration and operation of microgrids are immense. One such challenge is to ensure stable operation during faults and various network disturbances. Switching from an interconnected to an islanding mode of operation is likely to cause large mismatches between the generation sources and loads, which in turn could lead to severe frequency and voltage control problems. Maintaining stability and power quality in islanding mode requires the development of sophisticated control strategies that include all aspects of both the generation and demand sides as well as energy storage.

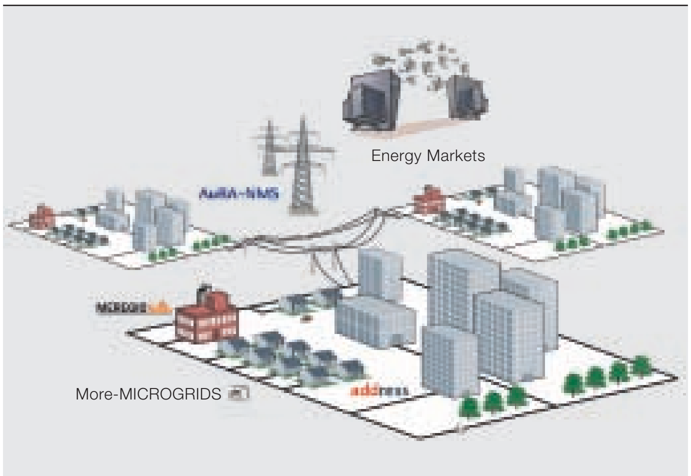
Protection is another key challenge. When a fault occurs on the grid, the microgrid should be isolated from the main utility as quickly as possible to protect the microgrid loads. If the fault lies within the microgrid, protection functions should be able to detect the normally low short-circuit currents provided by the power-electronic based micro generators in order to isolate only the most necessary part of the microgrid. The unique nature of microgrid design and operation requires an investigation of the various aspects of low-voltage network protection, such as new concepts of relaying.

In ABB's view a smart grid is an infrastructure that puts the emphasis firmly on active rather than passive control.

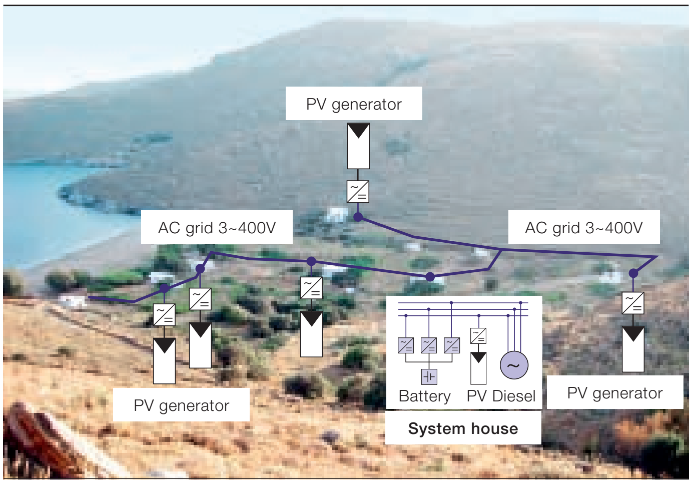
More Microgrids

To meet these challenges, a European Commission project known as Advanced Architectures and Control Concepts for More Microgrids – More Microgrids aims at providing solutions to support the

1 Projects financed by the European Commission focus on integrating distributed generation and improving energy efficiency.



2 A low-voltage Gaidouromantra microgrid deployed in Kythnos Island, Greece.



widespread deployment of microgrids. In particular, the project investigates:

- Centralized and decentralized control strategies to determine which provides more efficient voltage and frequency control and less mismatch between various micro sources and loads in cases when islanding is required.
- Novel protection paradigms suitable for microgrid operation.
- The technical and commercial aspects of integrating multiple low-voltage microgrids with a large number of active participants, such as small scale generators, energy storage devices and flexible loads, via a medium-voltage distribution grid.
- The operational and environmental benefits and the impact of microgrids on the future replacement and investment strategies of transmission and distribution infrastructures at regional, national and European levels.

Currently eight pilot microgrids are available to enable the experimental validation of various microgrid architectures, control strategies and protection algorithms → 2.

The More Microgrids project started at the beginning of 2006 and will end in January 2010. The consortium involved in the project comprises 22 manufacturers including ABB, Siemens, ZIV and SMA Solar Technology; power distribution utilities such as Liander, MVV and EdP; and research teams from 12 European countries.[1] It is co-funded by European Commission's sixth framework program (FP6) for research and technological development with a budget of 4.7 million euros ($6.4 million). ABB is a member of the steering committee and sits on the manufacturer's board. It is coordinating the work package that develops microgrid protection schemes and functions as well as novel concepts, such as DC microgrids. In addition, ABB is heavily involved in analyzing the idea of using microgrids as a provider of ancillary services.

Finding ways of better managing real-time operations of electricity distribution systems is key to improving the quality of the supply offered to customers. However, the almost certain need to connect small-scale renewable energy sources to a vast and complicated infrastructure that is considered passive and too expensive to replace prematurely is a technical barrier that must be overcome. In the grid of the future, overall central control will not be realistic and therefore suitable ways of delegating control need to be found.

This search is currently underway and is being carried out by a team consisting of three power industry giants (ABB, EDF Energy and Scottish Power) and eight universities, including Imperial College London who is acting as the principal investigator. The project, known as Autonomous Regional Active Network Management System (AuRA-NMS), is sponsored by the Engineering and Physical Science Research Council (EPSRC) in the United Kingdom and has a total budget of 5.46 million pounds[2] ($9.13 million).

AuRA-NMS

Existing network control centers are typically semi-automated and semi-manual in which network operations and analyses, such as load flow studies, reconfiguration, short-circuit analysis and outage management are performed by the network operator. The AuRA-NMS project explores ways of gradually devolving control authority from these centers and replacing them with peer-to-peer networks with distributed intelligence (ie, automatic controllers/decision makers) at each substation. The controllers could open and close remotely controlled switches to reallocate loads to different parts of the network and take different voltage correction actions. In addition, they could control the charging status of energy storage systems as well as the

> While true smart grids are still a vision of the future, the technologies and standards that will be needed have been under development at ABB for some years.

Footnotes

1 Research teams include those from the Universities of Athens, Porto, Manchester, ISET, Labein and CESI.

2 This figure includes the allocated contribution of the collaborating industrial partners.

outputs of distributed generation. An effective communication system would be required to obtain feedback information and to allow controllers with only a partial view of the system to cooperate in determining an optimal set of actions in the event of a fault, a voltage excursion or a generator whose output is being limited by network constraints. The controllers located in primary substations would coordinate with each other to facilitate secure network operation during normal and abnormal operating conditions. The control functions in these substation controllers need to be able to handle the challenges faced by the two distribution network operators arising from changing regulations and the increase in the number of distributed generation sources in their networks.

ABB's role as project manager in the AuRA-NMS project is to provide expertise on substation automation and distribution state estimation. In addition, the substation controllers, COM615, as well as the SVC Light® with Energy Storage system are supplied by ABB.

The project started at the end of 2006 and will finish in early 2010. Pilot installations are currently installed in some of the EDF Energy substations in England.

In the not too distant future, it is envisaged that renewable energy resources, such as wind and solar power, will be exploited to satisfy a large part of our energy needs. However, unpredictable weather conditions can potentially wreak havoc with the power supply. This need not be a problem if an appropriate response to a sudden change in the power supply is built into the distribution system. While storage elements in the grid will help compensate for any variance, household energy consumption could be optimized by an "energy box," which would react by briefly shedding unimportant appliances or equipment to ensure uninterrupted power to critical ones during power shortages. If done properly, this approach, called active demand, can increase the flexibility of the energy system, which in turn will enable a greater utilization of renewable energy sources. Providing the ideas necessary to enable active demand is the aim of another European Commission project called "Active distribution networks with full integration of demand and distributed energy resources," otherwise known as ADDRESS.

ADDRESS

The primary goal of ADDRESS is to enable active demand. Active demand refers to the possibility of domestic and small commercial customers to influence grid operation by modulating their power demand. The key concept investigated is that of the Aggregator, a business which would represent a large group of small consumers in the electricity market. An Aggregator would sell modifications of their consumption profiles as a service to other power system participants, such as retailers, provide distributed system operators (DSO) and balance responsible parties (BRP). In order to achieve this, the project will develop a technical and commercial architecture to implement the concept, as well as investigate measures to motivate consumers to participate in the power system. The technical architecture consists of a network control and communication architecture and an interface (ie, the energy box) to the consumer. Algorithms are being developed for the optimization of medium- and low-voltage network operation and of energy use on the consumer premises, and to allow consumers to select services that enable them to reduce consumption in the short term or shift it to hours during which prices are lower. The commercial architecture includes a description of the services an aggregator may offer on the electricity market.

> By actively pursuing collaborations with external partners, ABB will be able to provide customized smart solutions.

ADDRESS started in June 2008 and will continue for four years. The proposed architecture will be demonstrated at three test sites in France, Spain and Italy. Five energy companies, EDF, Iberdrola (Spain), ENEL (Italy), ABB and KEMA (Germany), together with the Universities of Manchester and Cassino constitute the main partners in the project and are supported by a further 18 partners from around Europe. The project is co-funded to the tune of 9 million euros ($13.5 million) by the European Commission's seventh framework program (FP7/2007-2013) for research and development. ABB is a member of both the management and technical boards and leads the work package responsible for the development of the communications architecture. In addition, the company contributes significantly to the development of new algorithms for network operation.

The mitigation of climate change is a long-term issue that calls for significant changes in the way industry and society at large produce and use energy and electricity. For its part, ABB has been committed to helping its customers use energy more efficiently and reduce their environmental impact through a broad array of products, systems and services [3]. It continues this commitment through its involvement in yet another European consortium project, whose objective is to create an optimized and sustainable power network that reduces CO_2 emissions to as close to zero as is technically feasible to produce a so-called minimum emissions region or MEREGIO as the project is commonly known.

MEREGIO

MERIGIO is a collaborative project between ABB, IBM, SAP, EnBW (one of Germany's largest utilities), Systemplan Engineering and the University of Karlsruhe. It was one of the six winning proposals submitted to the "E-Energy: ICT-based Energy System of the Future" competition sponsored by the German Federal Ministry of Economics and Technology.

Taking the Karlsruhe/Stuggart[3] area of Germany as the "model" region, the project makes use of information and communication technology (ICT) in its bid to eliminate the CO_2 emissions caused by heating and electric power consumption. A thousand smart meters with bidirectional broadband communication interfaces will be installed as part of the pilot

Footnote

3 The Karlsruhe-Stuttgart region of southern Germany is one of the most densely populated areas of the country and widely considered Europe's biggest manufacturing and high-tech hub.

project: 800 will be shared among household and industrial consumers, 150 for generation units and 50 for energy storage systems. A certificate showing regional energy efficiency will be used to inform industrial and household consumers of the size of their CO_2 footprint.

Technically, the efficient use of an electric grid is achieved by optimally integrating the many sources of distributed generation and the active management of electrical demand. To achieve the latter, the grid operator needs to be provided with real-time information about the entire power network in terms of supply and consumer demand. The communication infrastructure employed in the pilot will give the operator the information needed to control the network by predicting power flow and responding rapidly to changing situations. In addition, the operator can transmit time-variant tariffs – or price signals – to consumers, allowing them to respond by adapting consumption according to energy price and availability. [4]

ABB's role in the project is to provide the expertise in network control and distribution automation. In particular, this includes the detection of bottle necks and the optimization of network operation by, for example, minimizing switching operations during maintenance, and the provision of forecasting nodal generation and demand. All these can be achieved by applying the various sophisticated algorithms. The accuracy of a forecast will depend on the quality of the input data the algorithm receives. In other words some algorithms receive (real-time) data such as voltage and current values from network devices as well as information from the smart meters. Moreover, ABB's network management system will also interface with market and trading systems[5] to ensure that market-based measures, such as market splitting, can be applied both to avoid bottlenecks and analyze data on future energy trades in order to predict load flow in the distribution network.

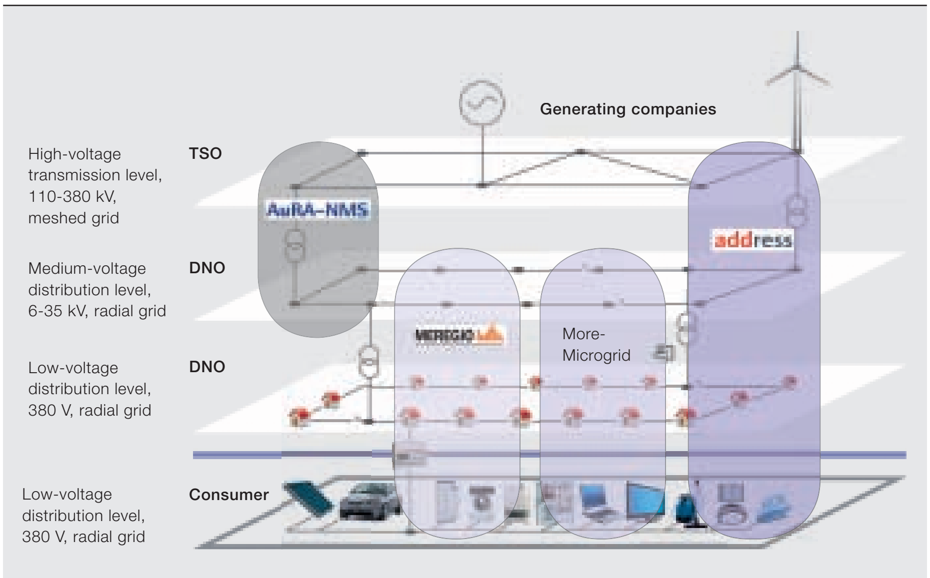
The four-year MEREGIO project started at end of 2008 and the one-year field test of the complete system with customers is planned to start in 2011.

Four projects, one vision

For ABB, these projects not only provide up-to-date and firsthand information on the technical and regulatory needs of utilities and network operators, but they also enable fruitful collaborations with other well-known institutes working on state-of-the-art smart grid technologies → 3. The results from each of these projects complement each other and can be applied to a wide variety of ABB products and solutions to satisfy different customer needs.

Although the grid of the future is being called the smart grid all over the world, it is clear that there will be significant differences in the challenges faced in introducing these technologies in different places. This means the smart grid will probably be different in each location. By actively pursuing collaborations and cooperation with utilities, universities and other participants in the energy sector, ABB will be in a position to provide solutions that are appropriate to each individual customer situation. A truly smart strategy.

3 The grid of the future? Collaborations are working to transform the old "traditional" system into an intelligent, more effective and environmentally sensitive network.



Cherry Yuen
Alexandre Oudalov
Andrew D. Paice
ABB Corporate Research
Baden-Dättwil, Switzerland
cherry.yuen@ch.abb.com
alexandre.oudalov@ch.abb.com
andrew.d.paice@ch.abb.com

Klaus von Sengbusch
ABB Power Products
Mannheim, Germany
klaus.von-sengbusch@de.abb.com

Footnotes

4 This is in effect a verification of a concept that comes into effect in Germany after 2010 whereby utilities should offer tariffs to consumers according to current network operation conditions.

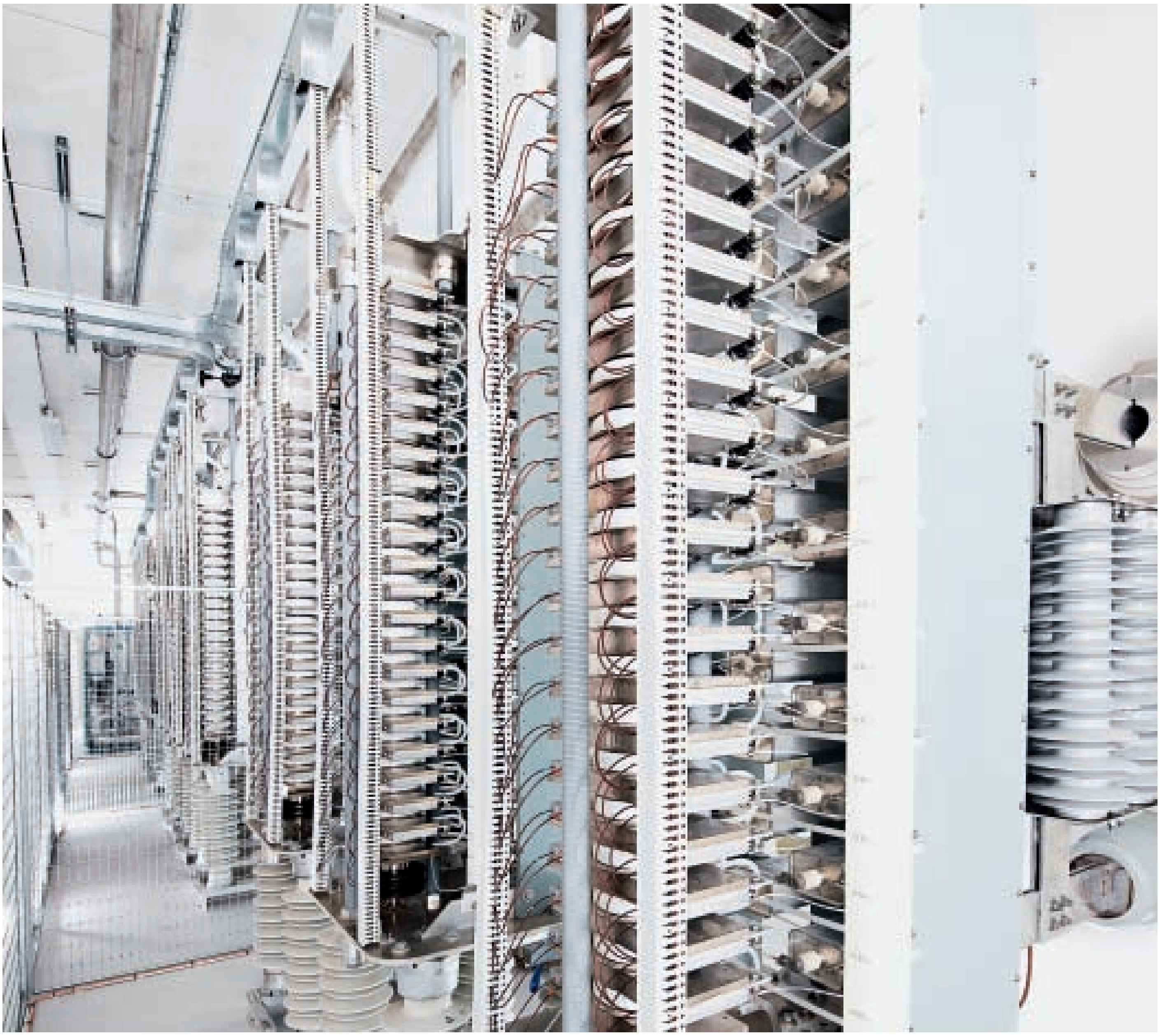
5 These systems are also an integral part of the MEREGIO project.

References

[1] The White House (2009, October 27). President Obama announces $3.4 billion investment to spur transition to smart energy grid. Retrieved November 11, 2009, from www.whitehouse.gov/the-press-office.

[2] The European Commission (2005). Toward smart power networks: Lessons learned from European research FP5 projects. Retrieved November 10, 2009, from http://ec.europa.eu/research/energy.

[3] Nordstrom, A. H. Challenges and opportunities aplenty: How to meet the challenge of climate change. *ABB Review* 3/2009, 6–10.



Securing power

Mitigation of voltage collapses in large urban grids by means of SVC

ROLF GRÜNBAUM, PETER LUNDBERG, BJÖRN THORVALDSSON
– Recent blackouts in Europe as well as the United States have focused attention on the importance of a secure and reliable supply of power to homes, public institutions and industry. It is now recognized that a significant number of grids are plagued by underinvestment, exacerbated by the uncertainty of roles and rules within the electricity supply industry brought about by deregulation. For instance, the unbundling of power generation and transmission in recent years has meant that grid companies can no longer rely on generators for reactive power, ie, transmission suppliers may have to provide their own var (volt-ampere reactive). The fast and adequate supply of reactive power is required to maintain stable voltages, especially when high percentages of induction motor loads, such as those created by air conditioners in urban areas, are dominant in the grid and during system faults. SVCs (static var compensators) are a solution well adapted to meet the challenges in question.

A vital characteristic of the SVC is its ability to provide reactive power in grids for a variety of situations, thereby helping to maintain, or, in the most difficult cases, restore stable operating conditions to grids. The article focuses on a current case where SVCs are used successfully for dynamic voltage stabilization in power grids dominated by heavy loads with a large percentage of induction motors for air conditioning.

SVCs are part of the FACTS (flexible AC transmission systems) family of devices that are applied to power systems for a variety of tasks, with the aim of improving grid performance.

A shortage of reactive power is often the cause of a voltage collapse in the power grid. Typically reactive power is needed to maintain proper voltage levels in a power system. However, reactive power cannot – nor should it – travel over long distances, because it is associated with power losses as well as voltage gradients. Reactive power should therefore be provided where it is needed (ie, at load centers).

Reactive power is consumed by loaded lines. When a fault occurs in a power system, such as a short circuit, the affected line is disconnected and the remaining lines pick up the flow. Reactive power is then consumed to an increasing degree. If the reactive power supply is limited, the increased loading on the line will cause a voltage drop over the system. If reactive power is not provided at this time, the voltage can fall precipitously. The transmission system can no longer transfer electrical energy and a system blackout will follow.

It is apparent that provision of the right kind of reactive power (with proper dynamic characteristics) at the right moment and at the right locations provides potent methods to prevent, or at least limit, blackouts. This is where ABB's SVC can play a critical role.

Fast var, slow var

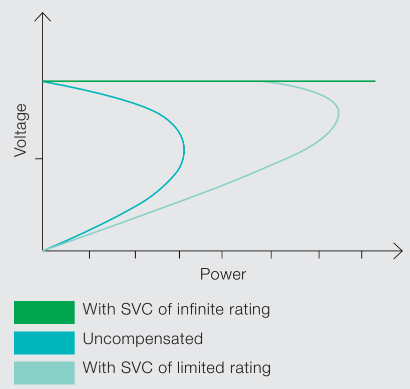
Reactive power can be supplied, not only by SVC, but also by MSCs (mechanically switched capacitors). There are, however, some vital distinctions to be made. While the SVC provides fast vars, an MSC is a provider of slow vars. This means that the MSC is very useful in situations where there are no particular requirements on dynamic response or frequent operation, such as steady-state voltage support to follow 24-hour load patterns. For more demanding applications, MSCs fall short, and SVCs (or indeed STATCOMs [1] will be needed.

Dynamic voltage stability

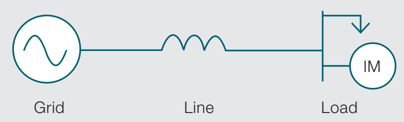
The introduction of an SVC at a critical load point will serve as a powerful tool for dynamic voltage support that will enhance the stability margin. The ability of an SVC to maintain a constant voltage at the load point of a certain grid configuration is dependent on the SVC rating and the size of the load. This relationship is shown in → 1.

Controlling the undervoltages produced by faults and overvoltages produced during light or no-load conditions are key features of SVC operation. A generic case is shown in → 2. The load center is fed through a transmission line and the load consists, to a large extent, of induction motors (IM), which are sensitive to undervoltage situations. In this case both active and reactive power to the load must be supported through the transmission line. Quite apart from the ohmic losses this will generate in the system, it will also show up as a variety of challenges during faults in the system. In the following section, these challenges are described.

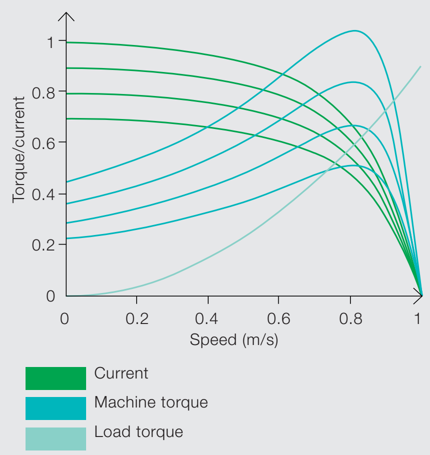
1 Voltage variation at a load busbar as a function of loading with and without SVC



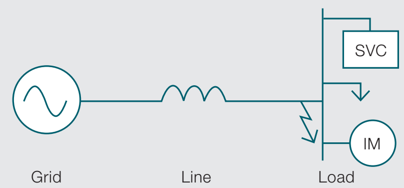
2 Single-line diagram of generic system



3 Load torque and machine torques as functions of speed and machine currents



4 SLG close to the load



Footnote

1 A STATCOM (static synchronous compensator) is a power electronics voltage-source converter used on alternating current electricity transmission networks that acts as either a source or sink of reactive power.

Undervoltage control
Undervoltage situations can occur at generator outages or faults in adjacent feeders. These faults are typically temporary, clearing after 100 to 150 ms. During the fault, the voltage will drop by a varying degree. Two main cases of undervoltage can develop: one case during the fault, and the other directly after the fault has cleared.

If the SVC is very close to a three-phase fault, it cannot do much to help alleviate the voltage drop during the fault. For more remote faults or for single line-to-ground (SLG) faults, however, it might also be possible, to some extent, to support the voltage situation in the vicinity of the SVC since the SVC will continue to generate reactive power in the grid during the fault. Undervoltage situations are especially difficult when the load consists of a large percentage of asynchronous machines, such as motors for pumps or air conditioners. The steady-state relationship between the load torque and the produced electrical torque as a function of speed is shown in ➔ 3.

During the fault the asynchronous machines will slow, which will affect the system when the fault is cleared. In the most severe cases voltage recovery may be prevented in the grid after this kind of fault. Assume, for example, that an SLG fault occurs close to the load center as indicated in ➔ 4. With the help of an SVC that dynamically supports the situation during the fault by means of reactive power generation, the case can be solved. The SVC will give strong support to the grid, especially after the fault has cleared.

Overvoltage control
The overvoltage control works in a similar fashion to the undervoltage control, but is vital in load-rejection cases, where sudden loss of loads generates overvoltages due to reactive surplus from the generators, lines and cables in the system. The control speed of the SVC enables full support within one fundamental cycle and the SVC will consume reactive power to limit the voltage in the system. As soon as the load is back in the system the SVC will return to its original set point and support the system once again.

Static var compensator
An SVC is based on thyristor-controlled reactors (TCR), thyristor-switched capacitors (TSC), and/or fixed capacitors (FC) tuned to filters. A common design type is shown in ➔ 5.

A TCR consists of a fixed reactor in series with a bi-directional thyristor valve. TCR reactors are generally of air core type, glass fiber insulated and epoxy resin impregnated.

A TSC consists of a capacitor bank in series with a bidirectional thyristor valve and a damping reactor. The reactor also serves to detune the circuit to avoid parallel resonance with the network. The thyristor switch acts to connect or disconnect the capacitor bank for an integral number of half cycles of the applied voltage. The TSC is not phase controlled, which means it does not generate any harmonic distortion.

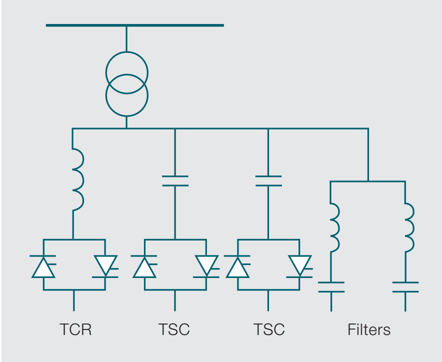
A complete SVC based on TCR and TSC may be designed in a variety of ways to satisfy a number of criteria in its operation on the grid. In addition, slow vars can be supplied in the scheme by means of MSC if required.

SVC characteristics
An SVC has a steady-state and dynamic voltage-current (V-I) characteristic as shown in ➔ 6. The SVC current/susceptance is varied to regulate the voltage according to a slope characteristic. The slope setting along with other voltage control equipment is important in the grid. It is also important when determining the voltage at which the SVC will reach the limit of its control range. A large slope setting will extend the active control range to a lower voltage, but at the expense of voltage regulation accuracy.

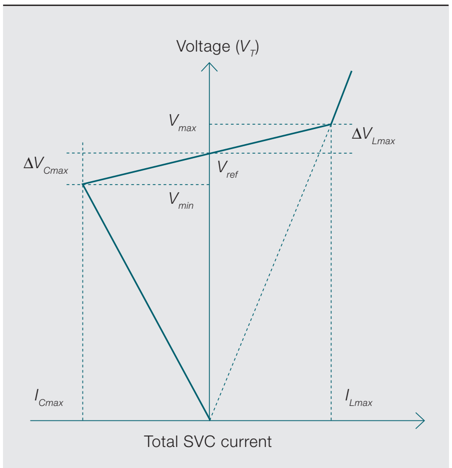
The voltage at which the SVC neither generates nor absorbs reactive power is the reference voltage Vref. This reference voltage can be adjusted within a certain range.

Preventing voltage collapse
The Saudi Electricity Company of the Western region of Saudi Arabia operates a power transmission system comprising 380 kV overhead (OH) lines and underground cables. There are numerous 380 kV / 110 kV bulk supply stations, feeding local 110 kV / 13.8 kV substations through mostly underground cable circuits. A simplified form of the grid is shown in ➔ 7.

5 SVC of TCR/TSC/Filter configuration

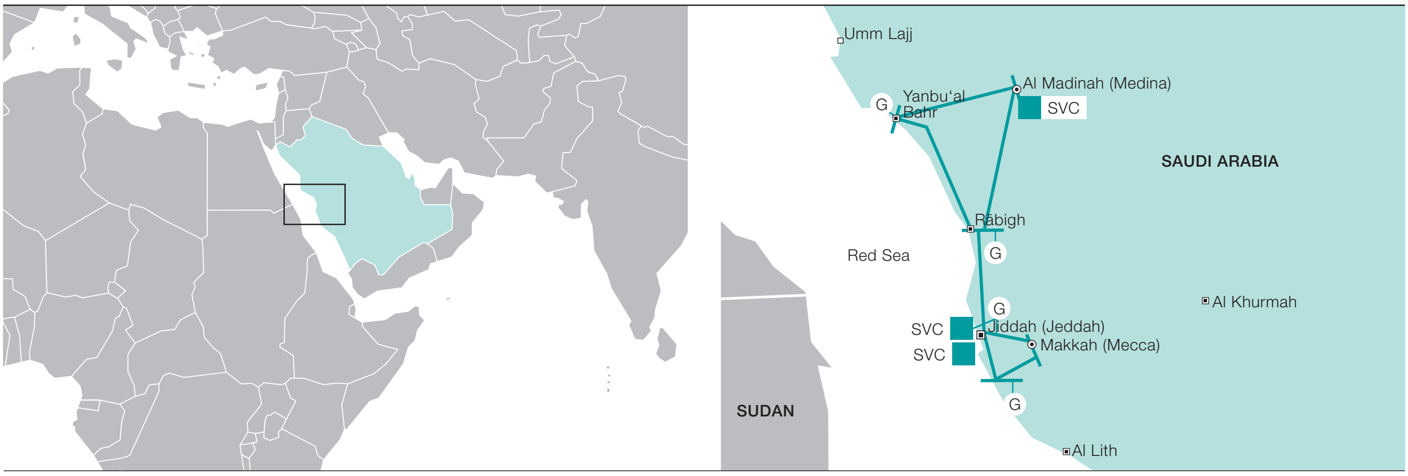


6 V-I characteristics of SVC



A shortage of reactive power is often the cause of a voltage collapse in the power grid. ABB's SVC can play a critical role in the provision of reactive power to prevent or limit blackouts.

7 Simplified grid of SEC Western region



Operating conditions in the Saudi power grid are special due to the hot climate, with up to 80 percent of the total load consisting of air conditioners. From a grid point of view, air conditioning is a particularly demanding kind of load, with slow voltage recovery, motor stalling or even voltage collapse in conjunction with short circuits in the transmission or subtransmission network. In the Western region, especially near the Red Sea, and with the major city of Jiddah and the cities of Makkah and Al Madinah as dominant load centers, grid stability is strained, particularly in summer and during the Hajj pilgrimage. Simulations have shown that the power system may not survive even SLG faults close to the load center during peak load conditions. To stabilize the situation, three large SVCs have been installed, with the explicit purpose of keeping the grid voltage stable as air conditioners all around the region are running at full speed ➔ 7 [1].

The power system has a few specific characteristics:
– A large difference between minimum and maximum (annual and daily) load
– Extremely high concentration of air-conditioning load
– High impedance 380 kV / 110 kV and 110 kV / 13.8 kV power transformers, to limit short circuit currents
– Somewhat remote generation

These characteristics affect the operation of the system. System performance and operational problems experienced were:
– Voltage control between peak load and off-peak load conditions
– Unacceptable voltage recovery after faults at medium-load conditions
– Voltage collapse situations at peak load conditions

A comprehensive reactive power planning study encompassing 380 kV, 110 kV and 13.8 kV levels was performed. The most important conclusions affecting the system planning and operation were:
– Faster fault clearing, where possible, reduces the dynamic reactive power requirement.
– AC motor stalling for SLG faults can be avoided by installing dynamic reactive power support.
– Dynamic reactive power support is needed only for a short period: during the fault and for about 1 s following fault clearing.
– Reactive power support is needed to counteract voltage fluctuations due to daily load variations.

The total dynamic reactive power demand was calculated at 3,000 MVAr (Megavolt-ampere reactive). Installing five SVCs with a rating –60 MVAr / +600 MVAr each (ie, 60 MVAr inductive to 600 MVAr capacitive) at five different 110 kV buses would solve the AC motor-load stalling problem and satisfy the daily load voltage control.

The first three SVCs at the Al Madinah South, Faisaliyah and Jamia substations were taken into service in 2008 and 2009. The remaining two SVCs are still to be purchased. Site views of the Faisaliyah ➔ 8 and Jamia SVCs are shown in ➔ 9.

Problem definition

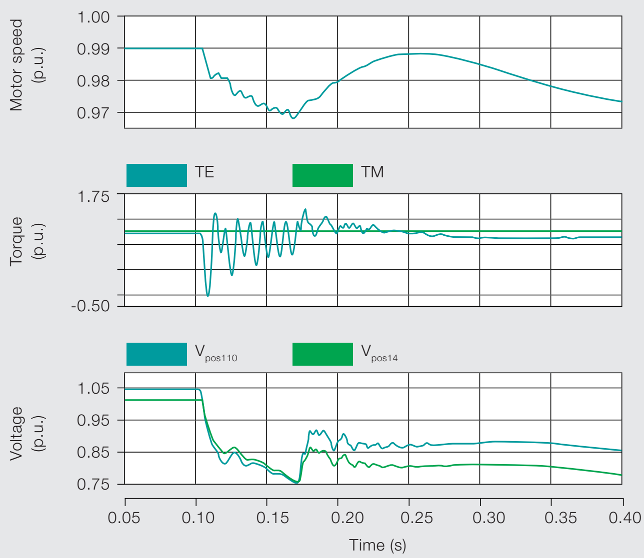
At an SLG fault in the vicinity of the city of Jiddah, on the 380 kV system or directly in the 110 kV system, the positive phase sequence voltage initially drops to 0.7 to 0.8 per unit (p.u.). Air-conditioner induction-motor flux decays and the motors lose electrical torque. Almost instantaneously the motors lose speed as the transient electrical torque becomes negative. During the rest of the fault time the electrical torque oscillates due to the imbalance, but with an average value below the load torque due to the reduced voltage. The loss of speed continues but with a smaller rate of change. At fault clearing the motors need to both remagnetize and reaccelerate. The resulting large active and reactive components in the load current give a big voltage drop in the source impedances. A large part of the impedance is in the 110 kV / 13.8 kV power transformers. In case of peak load conditions, the motors will have lost too much speed to be able to reaccelerate

SVCs provide a fast and adequate supply of reactive power to maintain stable voltages, especially when large induction motor loads, such as those created by air conditioners, are dominant in the grid.

8 Faisaliyah SVC

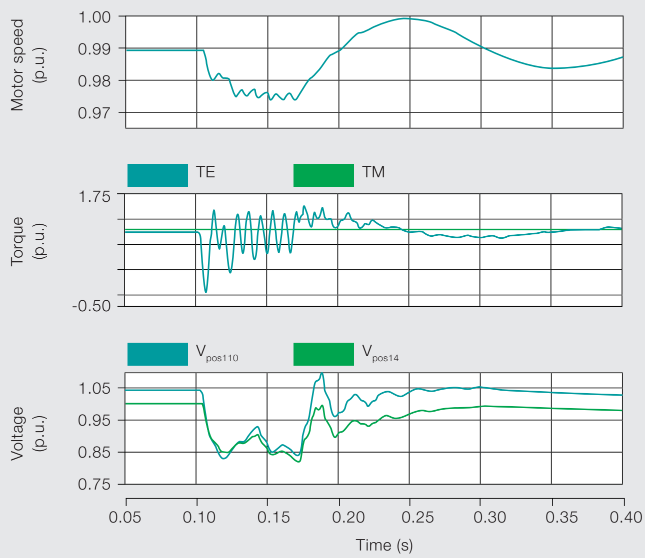
9 Jamia SVC

10 Motor speed, torque and 110 kV / 13.8 kV without SVC: unsuccessful voltage recovery



TE = Electrical torque
TM = Mechanical torque
V_{pos110} = Positive phase sequence voltage at 110 kV
V_{pos14} = Positive phase sequence voltage at 13.8 kV

11 Motor speed, torque and 110 kV / 13.8 kV with SVCs: successful voltage recovery



TE = Electrical torque
TM = Mechanical torque
V_{pos110} = Positive phase sequence voltage at 110 kV
V_{pos14} = Positive phase sequence voltage at 13.8 kV

following fault clearing, and voltage recovery is unsuccessful ➔ 10.

Countering motor stalling with SVCs

The way to prevent the motors from stalling is obviously to reduce the voltage drop during the fault and to restore the voltage as quickly as possible after fault clearing. Such a task requires a lot of reactive power support during a short period of time. Voltage support applied close to the motors gives the best results. The most efficient locations are in each 110 kV / 13.8 kV distribution substation on the 13.8 kV level. This would require installing a very large number of rather small SVCs. The practical solution is to install a limited number of large SVCs on the 110 kV level.

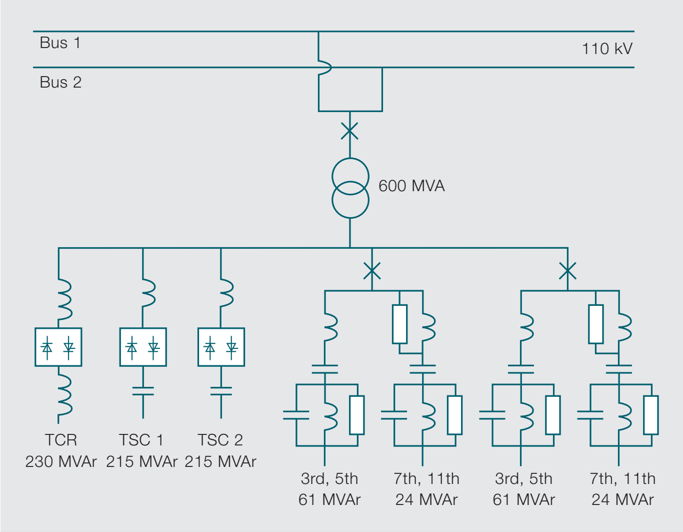
The initial drop in speed for the induction motors cannot be avoided by SVCs. It will take 1.5 cycles before the SVCs are fully compensating the voltage drop. With sufficiently large SVCs the voltage can be supported to such an extent that the motors do not continue to lose speed following the initial drop ➔ 11. A new "stable" operating point is reached. During the fault, it is very difficult to increase the voltage to the point at which the motors accelerate. It is important to stop or slow down the speed drop as quickly as possible. The sooner it stops the easier it becomes to reaccelerate the system following fault clearing. A shorter response time for the SVC means that fewer Mvars are needed. It has been shown in studies that the motors are almost impossible to reaccelerate after fault clearing in cases where the SVCs were not operating during the fault.

Directly at fault clearing, the voltage jumps upwards in a step. The reactive current to the motors increases instantaneously. In addition, a large active current is needed for reacceleration. In cases where the voltage at the motors remains severely depressed, the active current needed cannot flow and the voltage recovery in the system will be slow. In the worst case the motors will get stuck. By supporting the voltage, a more rapid recovery is made.

SVC performance

The three SVCs each have a rating of 60 MVAr inductive to 600 MVAr capaci-

12 SVC single-line diagram



tive power. They are connected to gas-insulated switchgear (GIS) substations on 110 kV. The nominal voltage on the SVC medium-voltage bus is 22.5 kV. There are two TSCs rated at 215 MVAr each, and one TCR rated at 230 MVAr → 12. The harmonic filters rated at a total of 170 MVAr are divided into two separate branches. The branches are connected to the MV bus by circuit breakers. Each filter branch consists of two double-tuned filters covering the 3rd, 5th, 7th and 11th harmonics.

Speed of response

When it comes to the speed of response for an SVC it is important to differentiate between "large signal" and "small signal" behavior. The large signal response is when the SVC responds to network faults causing a large system voltage change. This is typically a line-to-ground fault in the vicinity of an SVC, or a more distant three-phase fault. The small signal response is for minor changes in the system voltage such as the effect from tap changer action or connection/disconnection of a line reactor or a capacitor bank. For the utility-type of SVC, it is mainly the large signal speed that is of interest.

A utility SVC primarily controls the positive phase sequence voltage and in some special cases the negative phase sequence voltage. For control, the instantaneous voltage measurements have to be separated into sequence values and the harmonic components in the voltage must be removed. Both these actions require time. As a first approximation, the voltage processing can be seen as a first-order low-pass filter with a time constant of about 10 ms; the slope is the positive phase sequence current multiplied by a constant. Control action is by a PI (proportional and integrating) regulator (in many cases just an I regulator). It works on the difference between a set voltage and the actual voltage modified by the slope. The output is a signal that can be seen directly as a susceptance order to the main circuit. Thyristor valves can switch only once per half cycle and phase. A three-phase valve assembly can be modeled by an average time delay.

Typically, a response in the range of two cycles is achievable. This fulfills the requirement by the utility that the response time be no longer than 40 ms in a strong network. (In Saudi Arabia, the grid frequency is 60 cycles, ie, two cycles correspond to 33.3 ms.)

The stability of the control must be maintained at varying network strengths. Typically the short-circuit capacity varies by a factor of two between the strong and weak conditions. The regulator is trimmed to give a fast response at the weakest network condition. It is accepted that the SVC will be slower at the strongest network. In case the system becomes even weaker, automatic gain-reduction algorithms are activated.

The major task for a utility SVC is to quickly supply Mvar at severe voltage drops at network faults. The most frequent fault is a line-to-ground fault. The positive sequence voltage typically drops to 0.7 p.u. for a nearby fault and to gradually higher values for more remote faults. At such a large voltage deviation the SVC regulator very quickly (in about one cycle) reaches its limit. This time is essentially the same irrespective of regulator gain. The TSC valves will switch on at the appropriate point on wave [2] and the TCRs will cease conducting. The SVC will be fully conducting in 1.5 cycles. The TSC switch-on time may be longer depending on its precondition (charged or discharged). The most common condition is discharged capacitors.

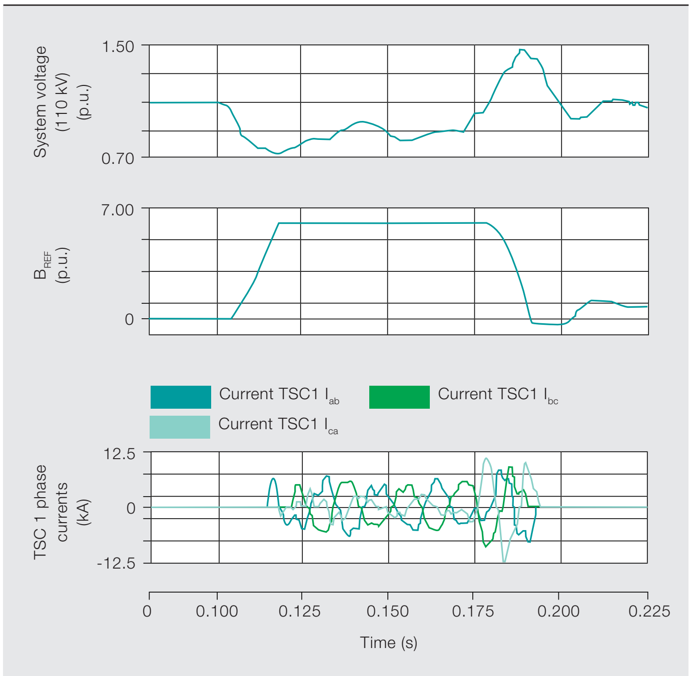
New control for faster voltage recovery

During a short circuit in the power grid the positive phase sequence voltage is depressed. The SVC runs fully capacitive. In case of a lightly loaded system, a temporary overvoltage may occur at fault clearing. The primary reason for the overvoltage is that the power system cannot absorb the reactive power generation from the SVC. A standard control system has to wait until the voltage has exceeded its set voltage before the regulator can start reducing the susceptance order to the main circuit. This inevitably results in an overvoltage with a duration of at least one cycle. In the studied system, voltages in excess of 1.5 p.u. may occur. Many SVCs around the world do not run in capacitive mode until after fault clearing because there were no efficient ways to solve this problem at the time when they were installed.

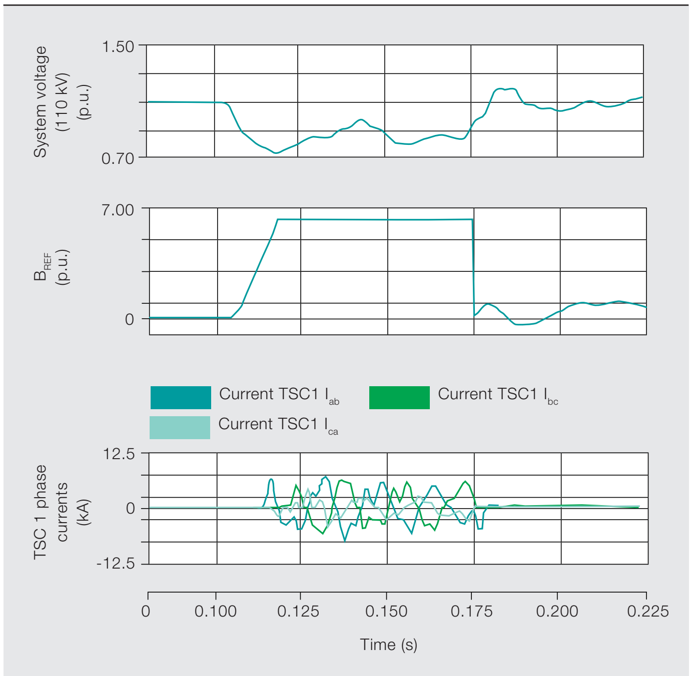
A simulation of the temporary overvoltage is shown in → 13. The need to switch the TSC out faster is evident. To improve the situation, a new control function was developed and implemented in the three Saudi SVCs where the TSCs are blocked at the first current-zero crossing following fault clearing. This approach has been shown to be efficient in simulations, however real data is still to come. The results obtained with the new control function are shown in → 14.

Motors are almost impossible to reaccelerate after fault clearing in cases where SVCs were not operating and in those cases where they were, fewer Mvars were needed when the SVC response time was short.

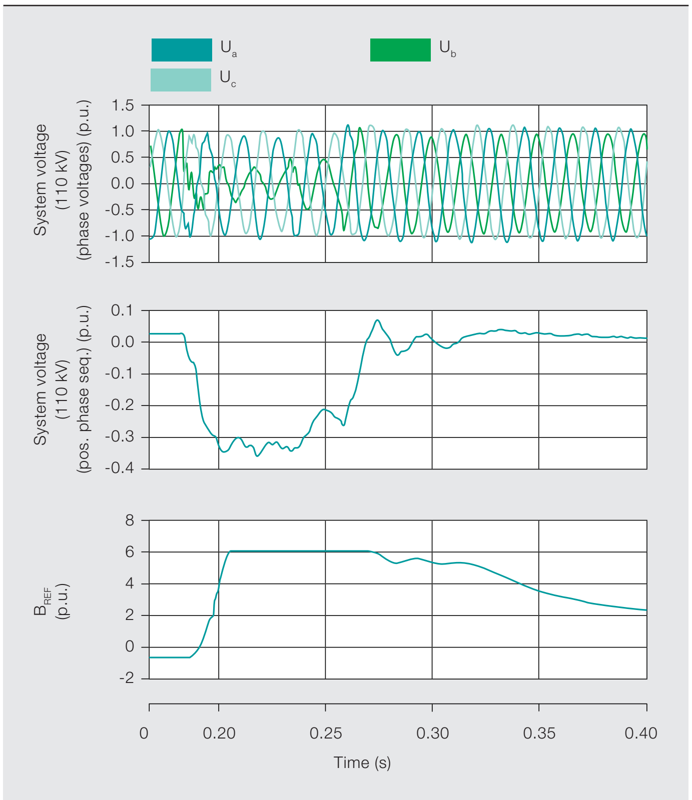
13 Temporary over-voltage: 1.4 p.u. over-voltage; TSC blocking at the 4th current zero crossing



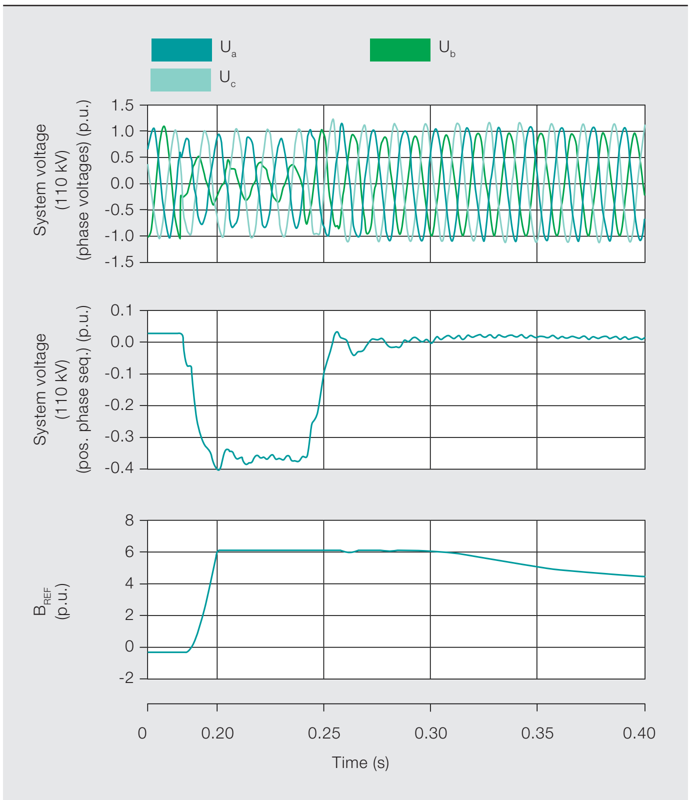
14 New TSC blocking function: over-voltage reduced to 1.1 p.u.; TSC blocking at the 1st current zero crossing.



15 TFR recording at Faisaliyah SVC



16 TFR recording at Al Madinah South SVC



17 Saudi SVC project

Several important conclusions can be drawn from the Saudi SVC project:
- Motor stalling or voltage collapse problems are evident in power systems with large induction motor loads such as those produced by the frequent use of air conditioners.
- SVCs provide efficient support for the positive phase sequence voltage during faults. The speed of induction motors can then be maintained at reasonable levels.
- SVCs must run at a high capacity during faults. The quicker the SVC response, the smaller the ratings needed. Very large ratings are required when the SVCs become active only after fault clearing.
- A short time rating is sufficient, ie, only a few seconds of operation is required.
- SVCs are robust and can run during faults and during fault clearing.
- The SVCs must be able to block TSCs immediately after fault clearing to prevent temporary overvoltages during light load situations.
- The typical SVC large-signal response time (from zero to full output) is 1.5 cycles with discharged capacitors.
- The typical SVC small-signal response time is 2.5 cycles for a strong power system, resulting in two cycles in the weak system without retuning.

Operational experience shows that the SVCs are efficient in supporting the positive phase sequence voltage during and following single-line-to-ground faults.

Operational experience

Three line-to-ground faults were experienced in the grid system in the summer of 2008, ie, during the peak load season. Two of the faults were in the Jiddah area (Faisaliyah) → 15 and one in Al Madinah → 16.

The SVC responded quickly to the fault, and became fully capacitive in 1.5 cycles. During the fault, the system voltage was constant or even increased slightly. It was noted that the fault-free phase voltages did not drop much after the initial dip. At fault clearing the faulted phase recovered instantaneously. The SVC reduced its output somewhat (about 100 MVAr) and ran at 500 MVAr for about four cycles; thereafter it gradually reduced its output to about 200 MVAr during the next five cycles. It remained at this output throughout the recorded period of 30 s. It is interesting to note that the faulted phase did not fully recover to its prefault value within the 30 s time period.

At the time of the fault, the phase B to neutral voltage instantaneously dropped. The measured positive phase sequence voltage in the SVC dropped with a time constant of about 10 ms. This is the time needed for phase sequence separation and harmonic filtering. The voltage regulator went fully capacitive in just a little more than one cycle. The time for the main circuit to run fully capacitive on all three phases was 1.5 cycles. The delay is due to the sampling effect – each phase can only start conducting on the zero crossing of their voltages. The TSCs started to conduct with a minimum of transients. At fault clearing the TSCs remained in service. The currents still contained a minimum of transients.

The fault in Al Madinah was similar to the one in Jiddah → 14. The major difference was that the fault in Al Madinah occurred at 8:45 a.m., compared with 4:45 a.m. in the previous case. At this later time the load in the system was heavier. There was larger asymmetry during the faults and one of the fault-free phases was depressed, while the third one remained unaffected. The recovery was somewhat slower and the SVC stayed at full output for a longer period of time. It should be noted that full capacity was needed only during some tenths of a second.

Operational experience shows that the SVCs are efficient in supporting the positive phase sequence voltage during and following SLG faults. The SVC reaction time is short and the TSCs behave correctly during the disturbances. Supporting the positive phase sequence voltage most efficiently means running all SVC phases fully capacitive. The disadvantage is that also the fault-free phases may be raised above the maximum continuous voltage. Such a rise could saturate the SVC power transformer; however, this problem did not develop as a result of the fault → 17.

Grid stability with fast SVC response

Power systems with large induction motor loads, such as air conditioners, present a high risk of voltage collapse or motor stalling, particularly in conjunction with faults. They tend to consume large amounts of reactive power, which should not be transmitted over large distances, since this increases the risk of voltage drops and causes active power losses. To maintain voltage stability in such circumstances SVCs can be used. To provide voltage stability in the grid, particularly in conjunction with fault situations, a fast dynamic response from the SVC is essential. There is typically a trade-off between dynamic response and the Mvar rating, ie, an increase in dynamic response offers possible savings in Mvar ratings while attaining the same favorable impact on grid stability.

Rolf Grünbaum
Peter Lundberg
Björn Thorvaldsson
ABB Power Systems,
Grid Systems/FACTS
Västerås, Sweden
rolf.grunbaum@se.abb.com
peter.lundberg@se.abb.com
bjorn.thorvaldsson@se.abb.com

Footnote

2 Point on wave is a kind of synchronous switching where there is an active choice of moment in the cycle when the switching is made.

Reference

[1] Al-Mubarak, A. H., Bamsak, S. M., Thorvaldsson, B., Halonen, M., Grünbaum, R. (2009, March). Preventing voltage collapse by large SVCs at power system faults. IEEE PSCE, Seattle, WA.

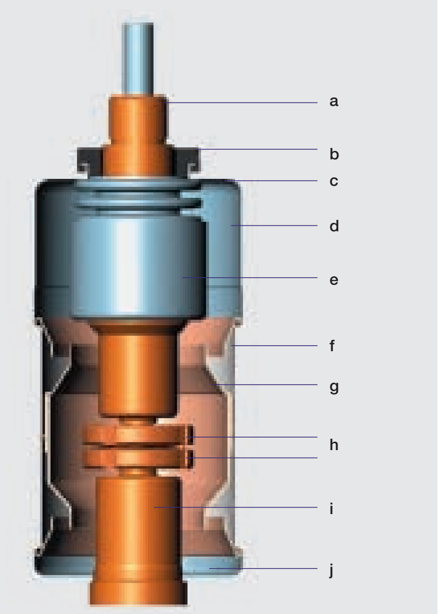
Breaking ahead of expectations

The PT1 pole sets new reliability and environmental standards in vacuum breaker technology

THORSTEN FUGEL, DIETMAR GENTSCH, ARNE KLASKA, CHRISTOPH MEYER

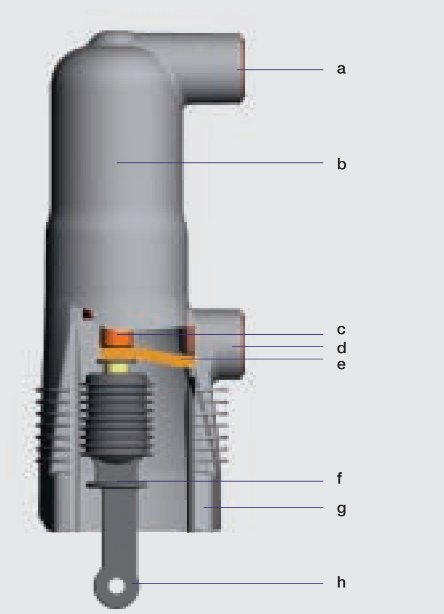
– More than a decade has passed since ABB invented the embedded pole for medium voltage applications. These interruption units offer the advantages of high dielectric strength, protection against environmental conditions and maintenance-free operation throughout the product's life. The latest step in this success story is the PT1 interrupter. Thanks to the adoption of thermoplastic material, the PT1 meets all performance aspects of its predecessor type while presenting numerous advantages, ranging from application parameters to its environmental impact.

1 Schematic of an ABB vacuum interrupter (type VG4)



a Stem / Terminal
b Twist protection
c Metal bellows
d Interrupter lid
e Shield
f Ceramic insulator
g Shield
h Contacts
i Stem / Terminal
j Interrupter lid

2 General design of an embedded pole



a Upper terminal
b Vacuum interrupter
c Stem
d Lower terminal
e Flexible connection
f Insulated push-rod with contact force springs
g Fixing point
h Connection to drive

A circuit breaker must fulfill three functional criteria: It has to handle nominal current, break short-circuit current, and block voltages exceeding the rated voltage level.

As the contacts move apart to interrupt a current, an electric arc is initiated between them. In an AC system, this arc extinguishes at the next zero crossing of the current. The contact mechanism is enclosed in a chamber → 1 containing (in today's medium voltage systems) a vacuum.

ABB has been supplying medium voltage vacuum interrupters (VIs) for over 30 years. While, in the late 1990s the market was divided more or less equally between vacuum and SF_6 technologies, vacuum has become the most dominant technology today. ABB currently produces approximately 350,000 vacuum interrupters annually and is a leading manufacturer in this area. Today, ABB's VIs handle nominal voltages of up to 40.5 kV and short circuit currents of up to 63 kA.

Besides managing the electric field inside the VI, the insulation must additionally withstand external power-frequency and BIL [1] voltages (up to 95/200 kV). This performance can be significantly reduced by environmental conditions (eg, dust). This is one of the reasons why, several years ago, ABB pioneered embedded pole technology. The present portfolio of ABB embedded poles covers the typical requirements of medium-voltage systems up to nominal voltages of 40.5 kV, currents up to 3.150 A and short-circuit currents up to 50 kA.

The vacuum interrupter and its terminals are completely embedded in epoxy resin. The upper → 2a and lower → 2d terminals are connected to the contact arm or the bus bar of the switchgear. As the lower contact must connect to a moveable part, a flexible connection is needed to conduct the current → 2e.

The moveable part is driven by an insulating push rod → 2f connecting to the breaker's drive → 2h. This rod is made of a polyamide material and contains a spring package. The lower part of the pole → 2g is fixed to the housing of the circuit breaker by means of four screws.

The main advantages of this technology (compared to an assembled or open-pole system) are its high dielectric strength as well as better protection against environmental influences, humidity and mechanical forces. The design is compact, robust and modular. Another important advantage is the fast and easy assembly of the pretested and adjusted poles on the vacuum circuit breakers. Embedded poles are suitable for different climatic conditions and are maintenance free for life. This means the vacuum within the interrupter and the insulation capability of the pole are retained for more than 30 years.

ABB is the inventor of this technology. With close to 1,000,000 units in field service, and an annual production of more than 200,000 pieces, the company is also the leading manufacturer of embedded poles → 3.

Despite the successful implementation of this technology and its huge advantages, ABB is continuously striving to improve it further. The newest member of the embedded pole family is the PT1. In contrast to its predecessors, the embedded pole is not based on epoxy resin but on a high-tech thermoplastic material.

Properties of thermoplastic poles

Function, form and process are among the decisive factors in introducing a new material (or class of material). The selec-

Footnote

1 The BIL (basic impulse level) voltage is an expression of the equipment's ability to withstand overvoltages caused, for example, by lightning and switching surges.

tion of a new material calls for an extensive analysis process.

Selection of materials

The systematic selection process for a material must verify the material's relevant characteristics as precisely as possible, taking into account the component's long lifetime (minimum 30 years). The investigation considers both physical and chemical properties and also considers material consumption aspects and production technology.

As the inner side of the embedded pole's housing is in direct contact with the ceramic surface of the VI, mechanical, thermal and dielectric properties are of particular significance for the PT1. Due to dielectrical considerations, density is the most important property here. Also, being an interface between polymer, ceramic and metal, and due to the large operating temperature range (– 30 °C – + 115 °C for operation, – 60 °C for storage) the difference of coefficients of thermal expansion have to be minimized, while mechanical stability and breaking elongation have to be maximized. The pole is furthermore used as an outer dielectric insulation when the VIs contacts are opened: Consequently, dielectric strength and comparative tracking index (CTI) [2] have to be maximized as well.

Thermoplastic and epoxy poles compared

Comparing thermoplastic poles of type PT1 with epoxy poles of type P1 revealed important differences as well as similarities.

Use of the thermoplastic material reduced the weight of the complete pole by approximately 35 percent compared with the P1. Looking at only the insulating material, the mass is in fact reduced by more than a factor of three. This was achieved by the following: The reduced density of the thermoplastic (12 percent), its significantly increased dielectric strength (approx. 50 percent), improved mechanical stiffness (approx. 100 percent) and strength (300 to 400 percent). These improvements furthermore allowed a reduction of the volume.

The high injection pressures used in manufacturing permit the thermoplastic material to use short glass fibers. This was not possible with the low-pressure injection of epoxy-resin based composite. In order to achieve a better mixing of components and a low viscosity, epoxy-resin based composites usually contain quartz powder (SiO_2 particles). Compared to such particles, and considering the same matrix material, fibers permit a higher mechanical stiffness and greater strength in the direction of the fibers due to an improved transmission of forces.

3 ABB embedded pole family

In order to offer customers a smooth transition from epoxy to thermoplastic poles, the outer dimensions of the epoxy poles were kept within those of the thermoplastic poles. Additionally, all functional dimensions are equal. This allows a full interchangeability of these components. The push rods and flexible connections were also kept the same.

Use of the thermoplastic material reduced the weight of the complete pole by approximately 35 percent compared with the P1.

In the transition, self-forming screws replaced the metric screws and brass inserts used with the epoxy poles. The new screws have already been used successfully with thermoplastic materials in other industries, eg the automotive industry. They are fastened with a torque of 35 Nm, assuring great stability (100,000 mechanical switching operations without a reduction in stability). This strength corresponds to an epoxy pole fixed with an M10-type metric screw requiring a fastening torque of 50 Nm.

Creep and relaxation tests were performed to verify whether, under operating conditions, (increased temperature and contact forces) the dimensions of the pole could change → 4. The poles were fixed on a steel plate and a force of 5,000 N was applied via the pushrod. This force is 1.7 times higher than the maximum loading in field service. For these experiments, the temperature was raised from room temperature (20 °C) to 85 °C; hence the increase of the pole length (0.5 percent) at the start of the experiment. Over the duration of the test (four weeks), the length of the pole remained constant. The length decreased again during cooling of the poles at the end of the experiment, leaving a residual elongation of max. 0.2 percent (which is close to the measurement accuracy). Hence, an elongation of the pole due to creeping or relaxation effects could not be detected.

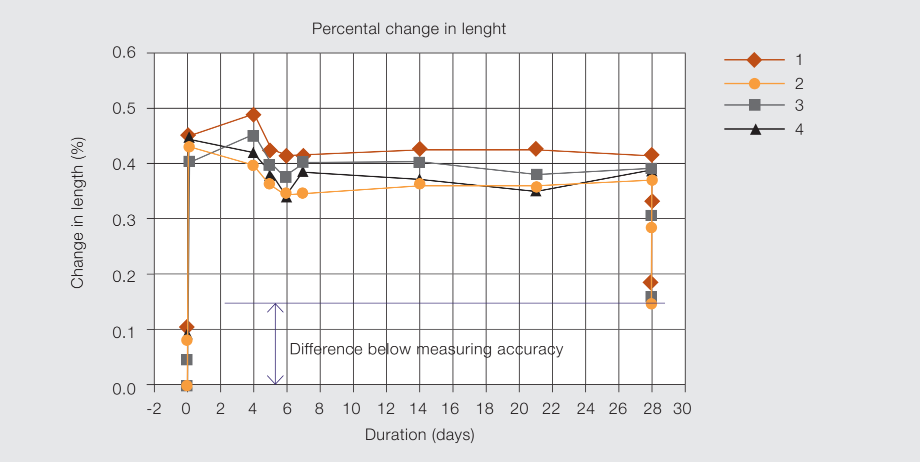
When considering the long-term stability of thermoplastic materials (especially polyamides), the water affinity of the material must be taken into account.

A connected vacuum circuit breaker in off position must still be able to block voltages as defined by the IEC standard even after a significant level of water absorption has occurred. In order to verify this, climatic tests were carried out at in-

Footnote

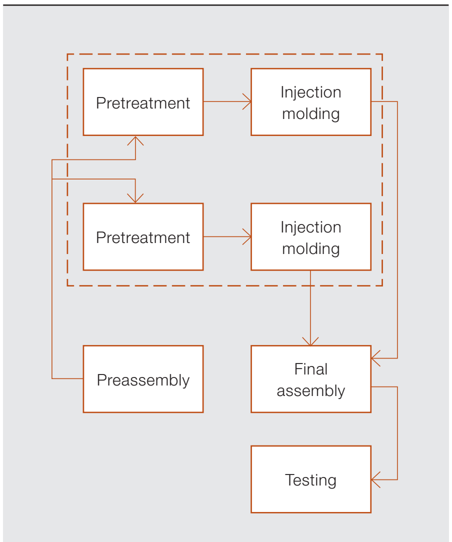
2 The Comparative Tracking Index is a measure of the electrical breakdown properties of a material.

4 Results of the creeping and relaxation experiments



These were performed with the embedded pole type PT1 at 5000 N and 85 °C, and show that no measurable deformation occurred. The jump at the beginning and end of the test period reflect heating from room temperature and the return to it.

5 General flow of production: thermoplastic vs. epoxy resin poles



6 Variations of the PT1 pole – version for 31.5 kA (6a) and 25 kA (6b)

6a 6b

creased temperature and humidity (increased water absorption for 500 h at 60 °C, 75 percent humidity), in parallel the poles were exposed to an AC voltage of 50kV. All tested poles demonstrated stability under these conditions.

Furthermore, a closing operation with a short-circuit current followed by a reopening had to be correctly handled by the pole. As the mechanical stability is significantly higher than for epoxy based composites, all tests were passed successfully with the new PT poles.

Production process

The overall concept for both the epoxy resin poles and the thermoplastic poles is quite similar. First, the inlay groups with the vacuum interrupter and terminals for the mold are pre-assembled. Then, these assembled groups are pretreated (eg, cleaning and testing). Subsequently, the groups are positioned in the mold, which is locked, closed and filled with the material. Due to the significantly different pressures during injection molding, the time required to fill the mold varies. For the epoxy resin-based composite, the filling is followed by the curing time, whereas for the thermoplastic it is followed by cooling. The general flows of production for the thermoplastic is shown in → 5.

The epoxy resin process is a chemical reaction, whereas the thermoplastic setting consists of a cooling-down period featuring crystallization of the material. The temperatures of the molds are approximately the same for both processes, whereas the injection temperatures of the raw materials are significantly different. For epoxy resin this is slightly above room temperature, whereas the melting temperature of the thermoplastic material is up to 300 °C. Consequently, heat needs to be applied during the epoxy resin process, whereas for the thermoplastic material, it must be dissipated.

As soon as the setting is complete, the mold is opened and the pole extracted. As the adhesion between thermoplastics, steel and other metals is generally very low, extracting the pole is not a problem. The poles are then forwarded to final assembly and testing. At this step, the push rod is added and the transport protection for the VI is mounted. The functional dimensions and the resistance of the pole are checked as a routine test.

The use of a fully automated modern injection molding machine with integrated sensors in the production of the thermoplastic VI improves on the already high process reliability of the epoxy pole.

The PT1 pole

The two available variants of the PT1 pole are shown in → 6.

The PT1 pole → 6a is capable of handling short-circuit currents up to 31.5 kA, nominal currents up to 1,250 A and voltages up to 17.5 kV. These values are similar to the ones of the corresponding epoxy pole type P1. The detailed characteristics are shown in → 7.

As the PT1 is used in medium-voltage systems, the general requirements are laid out in IEC 62271-100. These are all fulfilled or exceeded by the PT1. The pole fulfills the highest qualifications known by the standard, namely M2 (mechanical endurance), E2 (electrical endurance) and C2 (capacitive switching for back-to-back and cable switching operations).

Although this classification indicates that the PT1 fulfills the standard, it does not indicate the limit of performance. For example, concerning mechanical endurance, the standard requires 10,000 mechanical switching operations, whereas the PT1 is easily able to handle more than 50,000 operations without any maintenance.

7 Characteristics of the PT1 pole

Electrical Characteristics		1206-25 1706-25	1212-25 1712-25	1206-31 1706-31	1212-31 1712-31
Rated voltage	kV	12 / 17.5	12 / 17.5	12 / 17.5	12 / 17.5
Rated frequency	Hz	50 / 60			
Rated power-frequency withstand voltage (ms)	kV	… 42			
Rated lightning impulse withstand voltage	kV	… 95			
Rated normal current (ms)	A	630	1250	630	1250
Rated short-circuit breaking current (ms)	kA	25	25	31.5	31.5
Rated short-circuit making current (peak)	kA	63	63	80	80
Pole weight	kg	4.8	4.8	5.6	5.6
Contact force	N	2400	2400	3200	3200
Mechanical life CO-ops.		30,000			
Service life	yrs.	30			
CO-ops. at rated short-circuit breaking current		50			
Operating temperature	°C	-30 … +40			

Generally, it can be stated that the PT1 pole exceeds all requirements from standard point of view and is superior or equal in performance to existing embedded poles based on epoxy resin composites.

The use of a fully automated modern injection molding machine with integrated sensors in the production of the thermoplastic VI improves on the already high process reliability of the epoxy pole.

Tests performed

As already mentioned, the PT1 pole fulfills the requirements of IEC 62271-100 and passed all mandatory type tests. These tests were performed on PT1 fitted with the standard ABB vacuum circuit breakers type VD4 and VM1. Moreover, to render the demonstration fully functional, these tests were not carried out on standalone breakers but on breakers inside ABB switchgear type UniGear and enclosures type PowerCube.
This setup was used for all mandatory IEC type tests, ie, mechanical endurance, temperature rise, making and breaking, short-circuit testing (STC), as well as dielectric tests. Furthermore, the test for capacitive switching (back-to-back and cable charging) and electrical endurance have been carried out in this way. As the pole is intended for worldwide use, the requirements of these tests were adapted to cover the values required by most standards, eg, the power frequency test voltage was set to 42 kV, the BIL test voltage to 95 kV and 4 s have been applied for the STC. All these tests were carried out under the rules of the internationally recognized STL organization (Short-circuit Testing Liasion) and were therefore witnessed by an independent third party.

In addition to these, a large number of additional tests were performed, eg, an internal arc test according to IEC 62271-200. This was passed by the circuit breaker without any ignition of the pole. Furthermore, partial discharge (PD) measurements were carried out on a large number of poles. These tests have shown no PD on any of the investigated poles and thus confirm the well-known superior behavior of ABB embedded poles in the field.

Applications of the new pole type PT1

As a member of the ABB embedded pole family, the PT1 will be used on the current versions of both the VD4 and the VM1 → 8. It will be used to break short circuits, loaded and unloaded cables, transformers, motors, generators as well as capacitor banks. Furthermore, the pole will be sold as a components to OEM customers and as a replacement part for retrofit projects. Examples of application areas are shown in → 9.

From a customer point of view, the transition from the current embedded pole to the PT pole is extremely smooth and requires little effort. The PT1 is fully compatible to the existing P1 pole and has identical functional dimensions. To allow a smooth transition for OEM customers, ABB will not only provide support through the sharing of test reports, but also be issuing advice and declarations to help minimize the number of tests that need to be repeated in combination with an IEC-based test matrix. Once the circuit breaker is fitted within the customer's switchgear, the dielectric test is usually the only test that needs repeating

Advantages of the PT1 pole

Thermoplastic poles offer the same advantages as all other ABB embedded poles and fulfill highest quality requirements, eg, optimized dielectric insulation, protection of the VI and maintenance-free operation. In addition, they have several advantages compared to the current embedded poles and are therefore equal or superior in all aspects compared to the epoxy ones.

From an environmental point of view, PT poles present significant improvements over their epoxy predecessors, in terms of both their environmental-friendly production and recyclability [3]. To quantify this statement, a calculation was performed of the carbon footprint needed for the production of the poles. The analysis did not only consider the production of the poles themselves but also the pro-

Footnote

3 See also "For a better environment: Recycling opportunities for insulating components" on pages 10–16 of ABB Review 2/2009.

8 VD4-type circuit breaker with PT1 pole

9 Examples of application areas of PT1 embedded poles

– Power plants
– Transformer substations
– Chemicals industry
– Steel industry
– Automobile industry
– Airport power supply
– Shipbuilding (Marine applications)
– Power supply to buildings

The production of PT-type thermoplastic poles reduces CO_2 emissions by more than 50 percent with respect to their predecessors.

duction of the base material [4]. This calculation shows that the production of PT-type thermoplastic poles reduces CO_2 emissions by more than 50 percent with respect to their predecessors, corresponding to a reduction of approximately 3,000 tons of CO_2 per year considering the ABB production numbers.

Another advantage of thermoplastic materials is that the production process itself can be controlled very accurately, reducing variation of the properties of the material as well as the pole itself. Due to the mature technology of injection molding machines, a fully automatic production process is possible for PT poles, allowing detailed recording and full control of all relevant process parameters. This leads not only to increased traceability but also an improved quality control by statistic process control (SPC), improving the already well-known high quality of the present embedded poles.

Concerning technical parameters, the performance of the PT1 pole could be increased with regard to the P1 epoxy pole. The mechanical strength and the low temperature performance of the PT could be significantly increased, extending its operating limits. Furthermore, the fire load of the PT poles is significantly lower, presenting a further safety advantage for the end-customer. Additionally, the weight of the pole was reduced by 35 percent simplifying handling and transportation.

The PT pole, as the newest member of the successful embedded pole family of ABB, is the latest step in the development of this successful technology. They match or surpass all performance aspects of their predecessors while being totally compatible and making an important contribution toward climate protection.

Thorsten Fugel
Dietmar Gentsch
Arne Klaska
Christoph Meyer
ABB Calor Emag Mittelspannung
Ratingen, Germany
thorsten.fugel@de.abb.com
dietmar.gentsch@de.abb.com
arne.m.klaska@de.abb.com
christoph.meyer@de.abb.com

Footnote

4 Using original data that was either published or directly provided by the manufacturer of the material.

Fit at 50

THOMAS WESTMAN, PIERRE LORIN, PAUL A. AMMANN – Keeping fit and "staying young" are goals for many – including power transformers. Many of the world's transformers are reaching an age where these goals are becoming critical for their survival, and for the survival of the operating companies. The consequences of a transformer failure can be catastrophic. This is why operators demand high availability and a rapid recovery time after an outage. With an aging fleet of transformers and tight maintenance budgets, transformers remain in service well past their optimal life spans. The assumption that all are fit for an extended working life can be a dangerous gamble. When it comes to transformer asset management, an operator's main objectives are to reduce the risk of a failure and minimize the impact if a failure does occur. ABB's TrafoAsset Management™ provides just the support operators need to make intelligent maintenance decisions to face these challenges.

Keeping aging transformers healthy for longer with ABB TrafoAsset Management™ – Proactive Services

1 A nearly catastrophic failure damaged a transformer

2 The transformer in (1) has been remanufactured to a fully functional state

Power transformers, which are often the most valuable asset in a substation or plant, are indispensable components of high-voltage equipment for power generation plants, transmission systems and large industrial plants. Unexpected failures cause major disturbances to operating systems, resulting in unscheduled outages and power delivery problems. Such failures can be the result of poor maintenance, poor operation, poor protection, undetected faults, or even severe lightning or short circuits ➔ 1,2. Outages affect revenue, incur penalties and can cost a company its reputation and its customers.

The Institute of Nuclear Power Operations stated in 2002 that more than 70 events had been associated with large, main auxiliary or step-up power transformers (since 1996) [1]. Significant station impact occurred during several events and in addition over 30 reactor scrams (ie, emergency reactor shutdowns) as well as plant shutdowns and reductions in power delivery were associated with transformer events. The result: in many cases, lost production and expensive repairs.

The enormous costs of power transformer failures provide ample incentive for electric companies to ensure reliability and availability throughout the life cycle of these key assets. Transformers cost anywhere from $2 million to $4 million, and on the rare occasions they do fail, the financial impact can be even more significant – in extreme cases, they can leave a company facing financial ruin ➔ 3. In addition, as most countries have strict laws in place that control and regulate power supply, non-delivery penalties can be as high as 100 times the price of the energy itself.

3 Cost estimates of an unplanned replacement of a typical generator step-up transformer

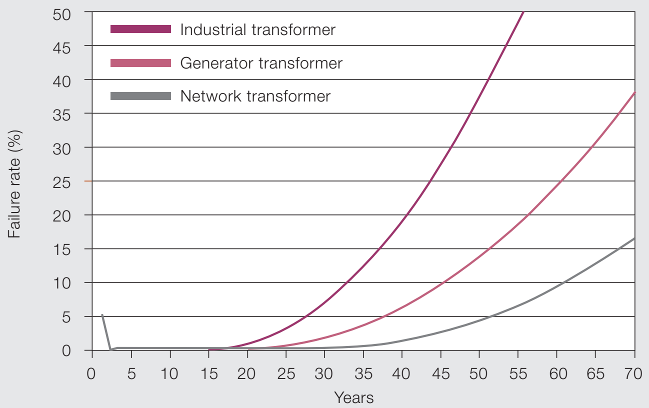
Environmental cleanup	$500,000
Lost revenue ($500,000/day)	$10 million
Installation labor and processing	$100,000 – $300,000
Additional modifications and site work	$300,000
New transformer unit	$2 million – $4 million

Transformer failures can cost up to $15 million, in addition to an operator's reputation. Source: Doble Life of a Transformer Seminar. Clearwater, FL, United States

An aging fleet

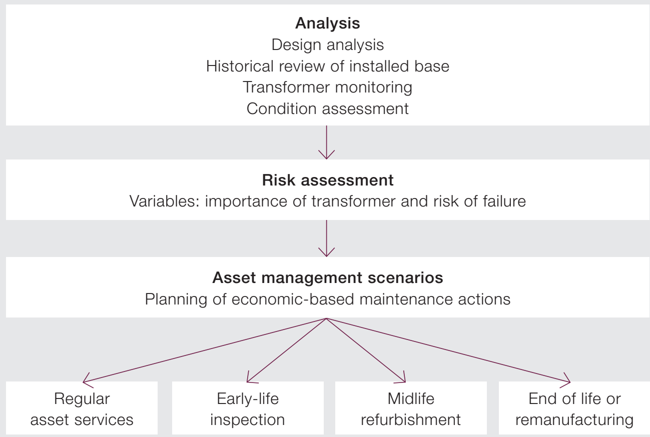
Although transformers are regarded as highly dependable equipment, the world's current transformer fleet is quite old. The average age for those in industrial plants is 30 years, and 40 years for those used by utilities. While aging transformers are generally not "ticking time bombs," their failure rates as well as their replacement and repair costs are steadily – albeit slowly – increasing. ➔ 4 shows the development of the failure rate of transformers installed in industrial plants (dark orange), generation plants (light orange) and transmission networks (gray). The risk development curves are steeper for industrial and power generation plants as the transformers in these installations tend to be used more intensively. While age alone does not increase the risk of unexpected failures, it generally is an indication of this risk. Risk of failure is heightened by other factors, including type of application and the tendency to load

4 Development of the transformer failure rate in three different applications

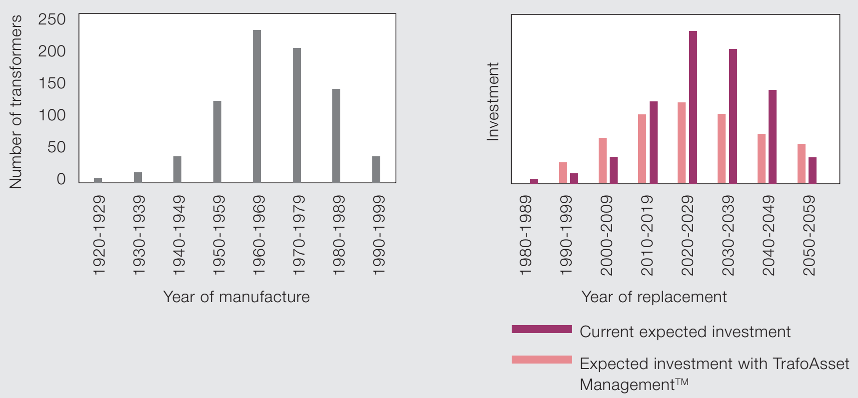


Source: CIGRE WG 12-05. (1983). An international survey on failures in large power transformers. ELECTRA, 88, 21-48.

6 Overview of ABB TrafoAsset Management – Proactive Services



5 Transformer investment then and now



5a The investment in new transformers peaked in the 1960s and 70s. Without optimized maintenance strategies and extended lifetimes, there will be another investment peak some 50 years later.

5b Implementing ABB's TrafoAsset Management program can help smooth the potential investment peak.

The world's current transformer fleet is quite old, and the cost of replacement has forced many companies to keep transformers operating beyond their recommended life span.

transformers to their maximum to meet the economic needs of the deregulated environment and competitive markets.

➔ 5 shows the investment peak in the 1960s and 70s for many companies in Europe and the United States. The cost burden when replacing aging equipment has forced many companies to keep transformers operating beyond their recommended life span in order to smooth the investment peak. This is only possible by optimizing the maintenance of the transformers and by implementing measures that extend their use.

At the same time, financial constraints demand an increased return on investment under reduced maintenance budgets and spending. The maintenance budgets are under increased pressure due to liberalization and deregulation, which have created a more finance-based focus. As a result, operators can no longer follow a simple time-based maintenance strategy that mitigates risks by doing everything, every year, for all transformers. Instead, they must implement a more sophisticated condition-based maintenance strategy: doing more maintenance for high-risk transformers than for low-risk transformers.[1] This requires reliable information about the status of the transformers.

ABB TrafoAsset Management – Proactive Services

Operational managers require special tools to support their strategic and day-to-day decisions, which address the above challenges and result in the right maintenance actions at the right time. Here, a clear trend has emerged: Managers are moving from using time-based

Footnote

1 High risk means high probability of failing and/or high impact of a failure on business results.

maintenance to implementing condition-based maintenance, where decisions are no longer driven by an average timeframe defined by past experience and observations, but instead take into account the actual condition of the equipment and the level of reliability required to fulfill its function. TrafoAsset Management supports this trend by focusing on three elements: analysis, risk assessment, and planning of maintenance actions based on asset management scenarios ➔ 6.

Analysis

The design data, the information in the installed base system, the results of the condition assessment and the maintenance history provide ABB with a 360-degree view of a transformer fleet. This data plays a pivotal role for ABB in the assessment management process. Not only is it important for minimizing the risk of failure, but it also provides valuable information for initiating maintenance work should a problem occur – that means quick maintenance and short downtimes.

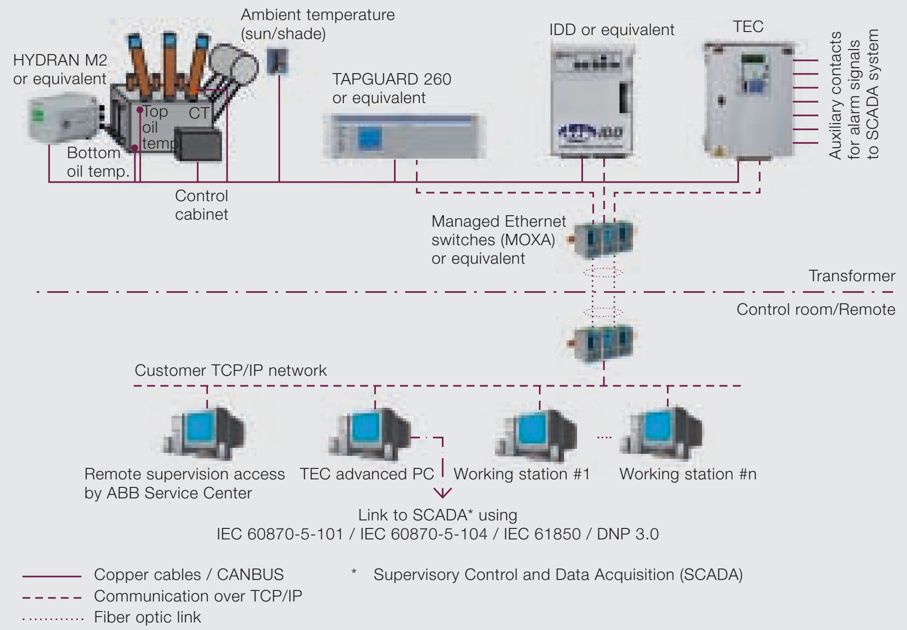
Design analysis

ABB has access to original designs for more than 30 legacy brands and design knowledge of nearly 75 percent of the installed base of large power transformers in North America – including those from Westinghouse, GE, ASEA and BBC – and other predecessor technologies. All new ABB transformers are built using the same design concept, which incorporates standardized, service-proven components and modules, ensuring flexible, dependable and adaptable transformer designs.

Historical review

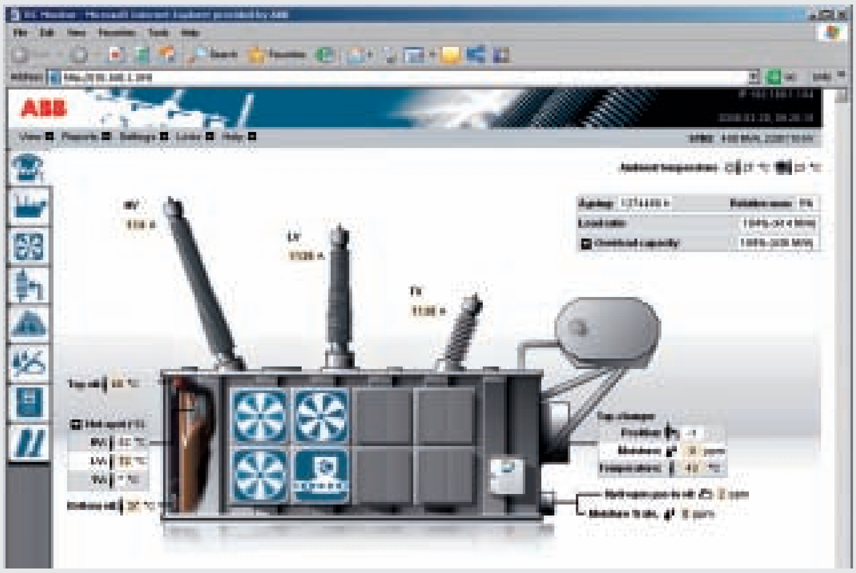
ABB's installed data system monitors a wide range of the company's products. A plethora of data on transformers is available and is continuously updated, eg, current owner details and history. The system provides an important basis for the proactive detection of problems. For example, an analysis revealed about 700 potential cooler problems in the installed base of transformers. The search focused on 10 to 600 MVA transformers that were over 20 years old and had oil- and water-type coolers. Many failed completely due to leakages in these cooling systems, and one such failure resulted in a three-month production shutdown and lost revenue for the operator. Using the information in the installed base system, operators were contacted proactively and the systems could then be checked regularly.

7 Structure of a transformer monitoring system



Source: Uhlmann O. (2009). ABB Transformer Service Engineering Solutions Portfolio Overview.

8 Transformer monitoring interface showing the status of important parts of the transformer



Source: ABB TEC Monitor. Retrieved January 2010 from http://tec2.vbelnat.se/.

Transformer monitoring

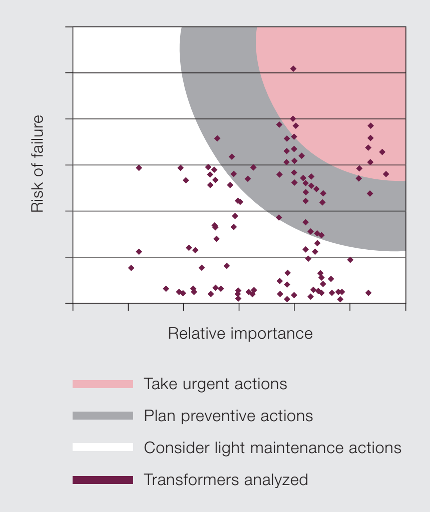
Transformer monitoring is becoming an essential component of transformer management. It serves as an early warning system for any fault developing in the main tank and in the accessories, allowing an operator to evaluate the severity of the situation. Multiple transformers are connected to the operator's network and can be monitored from a local control room or from remote working stations ➔ 7. Sensors measuring dissolved gases, moisture in oil, oil temperature, load current for each unit, and ambient

Footnotes

2 The risk of catastrophic failures can be reduced statistically from 0.07 percent to 0.03 percent through transformer monitoring [2].

3 First-level maintenance is the first line of problem management where information is gathered and symptoms analyzed to determine the underlying causes. Clear-cut problems are typically handled with first-level maintenance by personnel who have a general understanding of the products.

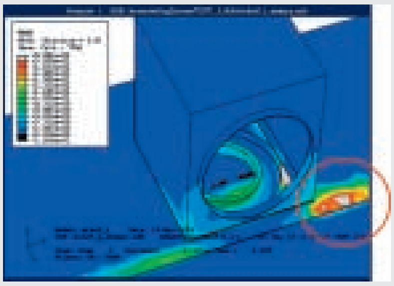
9 Typical output results of ABB's Mature Transformer Management Program™ (MTMP)



9a Step 1: Transformer fleet screening (of the whole transformer fleet) provides a risk assessment.

Plant 1 – Results of condition assessment and action plan						
	Mechanical	Electrical	Thermal	Accessories	Overall risk	Risk mitigation – Actions
TFO 2	Winding	Arcing	Heating		95	Visual inspection and repair in factory / rewinding
TFO 5	Tank			OLTC heating	80	Repair on-site and OLTC overhaul
TFO 1			Aged oil	Bushing	70	Oil regeneration / filtration and advanced diagnosis / change HV bushing
TFO 6		Arcing		Thermometer	50	Exchange top-oil thermometer / online monitoring of DGA
TFO 3				Silicagel	40	Exchange silicagel
TFO 7					25	Standard maintenance actions and controls
TFO 8					15	Standard maintenance actions and controls / 10% overload capabilities
TFO 4					10	Standard maintenance actions and controls / 15% overload capabilities

9b Step 2: Transformer design and condition assessment (of a subset of high-risk transformers) suggests concrete actions for each transformer.



9c Step 3: Life assessment/profiling (of a few transformers that had unusual results in steps 1 and 2) uses in-depth analysis to show the status of the transformers. The circled area indicates the need for immediate action.

temperature send data to the system via analog signals. The interface provides exact status information by generating a model of the transformer and its working condition and then comparing the measured parameters with the simulated values → 8. Discrepancies are detected and potential malfunctions and normal wear in the transformer and its ancillaries are indicated. The monitoring system also tracks transformer alarms, recording an actual event as well as the sequence leading up to the alarm to assist operators in determining the root cause. The benefits of monitoring are substantial. A CIGRE study has shown that transformer monitoring can reduce the risk of catastrophic failures by 50 percent [2] [2]. Furthermore, it has been shown that early detection of problems can reduce repair costs by 75 percent and loss of revenue by 60 percent, and that annual cost savings equal to 2 percent of the price of a new transformer – ie, approximately $40,000 to $80,000 – can be achieved [3].

The strength of ABB's Transformer Electronic Control, or TEC, monitoring system is that it receives all the relevant information from just a few multipurpose sensors. Other necessary parameters are calculated, adding only minimal complexity to the transformer. The end user is no longer forced to spend a lot of time sorting and interpreting data. In addition, the maintenance manager receives important information indicating the necessary actions for first-level maintenance.[3]

Condition assessment

ABB is the pioneer in highly customized condition assessment offerings. Its MTMP (Mature Transformer Management Program) is a state-of-the-art minimally invasive condition assessment process used to evaluate the power transformers in a customer's fleet and to identify which units need to be replaced or refurbished and when.

This process is implemented in three steps → 9. It starts with a high-level fleet assessment based on easily accessible data, such as unit nameplate data, oil and dissolved-gas-in-oil data, load profile and history of the unit (transformer fleet screening) → 9a. Next, a subset of the transformers identified in step one is examined in more detail (transformer design and condition assessment) → 9b. Modern design rules and tools are used to evaluate the original design, and advanced di-

Operators can no longer follow a simple time-based maintenance strategy that mitigates risks by doing everything, every year, for all transformers.

agnostic tests are performed to assess each of the principal properties of the transformer in a structured way. These include mechanical status, thermal status (aging of the insulation), electrical status of the active part and the condition of the accessories, such as tap changers, bushings, overpressure valves, air-dryer system, pumps and relays. The number of units identified for further analysis is typically limited to two or three out of a population of 100. At this stage (life assessment/profiling) → 9c, highly specialized experts analyze the units using simulation tools. Detailed data is then sent to the end users' operational managers, providing concrete information about whether a transformer can be overloaded, its nominal power or voltage rating increased or its lifetime extended [4].

Early detection of problems can reduce repair costs by 75 percent and loss of revenue by 60 percent.

Risk assessment

The risk assessment → 6 is based on two variables. The first, risk of failure, is estimated using the input from the analysis phase, ie, age or time in service, transformer's nameplate data (kV, MVA, etc.), application and loading practices, operational problems or issues, latest field-test data (eg, dissolved gas and oil analyses), availability of a spare transformer and spare parts. The second variable is the importance of a transformer in a network, indicating how much of the operator's system will be out of service if a particular transformer fails. By comparing these two variables, different levels of urgency for maintenance actions can be defined → 9a. The asset manager can then ensure that maintenance of high-risk transformers is prioritized.

Asset management scenarios

The risks for a transformer operator include not only the inherent technical risks but also the economic consequences of a possible fault, eg, the cost of non-delivered energy. With this in mind, ABB and a large operator co-developed an economical model that evaluates the life-cycle costs of a transformer fleet over a given period → 6. The model takes into account four categories of costs related to the cost of ownership over the lifetime: investment, maintenance, operational and consequential costs. Comparative investment scenarios and sensitivity studies can be run by varying the replacement year or maintenance of the unit. For each scenario, the process shows the associated net present value. An optimization routine can also be used to automatically minimize the life-cycle costs of the population. The process outputs a list presenting the optimum time to maintain or replace the individual transformers or transformer groups. The net present value of the whole population of transformers is determined by looking at the condition of each unit and the maintenance actions selected to improve their condition. The operational manager can then evaluate different maintenance scenarios and obtain a summary of the payback of planned maintenance actions. The novel aspect of the method is that not only are maintenance costs considered but economical benefits related to the impact of maintenance on reliability are considered as well [5].

Maintenance packages

ABB provides personalized recommendations and support using available data and state-of-the-art tools and maintenance packages, as shown in → 6. These include regular asset services, early-life inspection, midlife refurbishment and remanufacturing. For many operators midlife refurbishment has become very important as their transformers are aging. Midlife refurbishment is an extensive overhaul of a transformer to extend the remaining lifetime and increase reliability, and is typically performed after half of the expected lifetime. It involves several maintenance steps, including advanced diagnostics to check mechanical, thermal and electrical conditions. New or refurbished accessories such as on-load tap changers, bushings, pumps, temperature sensors, valves, gaskets and water coolers might be used. Refurbishment of the active part through, for example, cleaning, winding reclamping, connection retightening and installation of new parts, is often an aspect of a midlife refurbishment.

The benefits

Not knowing the risk structure of its fleet, a company tends to overspend on the maintenance of its low-risk transformers and underspend on the high-risk transformer → 10. Overspending on low-risk transformers is a "high-risk activity," as approximately 30 to 50 percent of maintenance actions are unnecessary [6]. But needless maintenance work can be avoided by implementing regular fleet assessments. The use of preventive or predictive maintenance is improving the transformer economy, which has been challenged by the limited maintenance resources associated with utility deregulation. Focusing the personnel and capital resources to the prioritized needs – with the priority based on the condition assessment ranking – can provide improved reliability at a fraction of the cost of traditional time-based maintenance programs.

It is estimated that life extension of five to 15 years can be achieved with properly focused preventive maintenance programs. The economic advantage related to preventive maintenance work and corrective actions can also be expressed in terms of extended life of the transformer assets – this is achieved by eliminating failures that might have occurred due to the lack of timely critical maintenance.

A proactive approach

ABB TrafoAsset Management provides operators with the information, expertise and maintenance tools they need to face the challenge of managing their transformer fleets. The result is improved asset management and lower risk of unexpected failures. In addition, the comprehensive range of data collected, from design to condition assessment, helps reduce the impact of a failure by enabling the transformer to quickly return to normal operating con-

ABB's TrafoAsset Management focuses on analysis, risk assessment, and planning of maintenance actions.

10 ABB TrafoAsset Management™ – Proactive Services in practice

One of ABB's customers, a major transformer operator, had been using a time-based maintenance strategy, which meant that it did not know whether the maintenance done on each transformer was adequate for its risk profile. In addition, the maintenance budget was under pressure due to market liberalization and it was unclear whether it would be sufficient for the risk structure of the transformer fleet.

ABB thus undertook a fleet assessment study of 128 individual transformers at 54 different substations to determine the risk of failure of each of the transformers in the entire fleet. The result was a prioritization of the fleet based on corrective measures, such as detailed design or condition assessment, diagnostic evaluation, inspection, repair, or replacement. With this information, the customer could then reallocate its resources to the high-risk transformers and reduce costs in the process.

The benefit of a condition-based maintenance approach is shown clearly in this example. The customer benefits from an optimized use of time and resources, which results in increased fleet reliability. Much more of the maintenance budget is now concentrated on the transformers that show a high risk of failure or are of high importance in the network. These transformers are maintained proactively in order to lower the risk of an unexpected failure.

Unit	Budget prior to fleet assessment	Budget after fleet assessment
11 high-risk transformers	$110,000 (9% of budget)	$245,500 (25% of budget)
47 medium-risk transformers	$470,000 (37% of budget)	$434,000 (45% of budget)
70 low-risk transformers	$700,000 (54% of budget)	$294,500 (30% of budget)
Total: 128 transformers	**$1.28 million maintenance budget**	**$974,000 maintenance budget**

Distribution of maintenance budget before and after ABB fleet assessment. The result of the optimized maintenance solution is a savings of 24 percent of the customer's maintenance budget ($306,000 annually) as well as having better maintained high-risk transformers.

ABB's asset-management approach provides a clear picture of the risk structure and the maintenance required to deliver needed asset reliability and availability.

ditions. By performing proactive maintenance based on the TrafoAsset Management method, operators benefit from a lower risk of unexpected failures as well as fewer penalties (for utilities) and loss of revenue (for industry) → 10.

The importance of asset management and proactive services based on condition assessments of transformers is paramount due to the increasing average age of the worldwide transformer fleet and the more demanding conditions regarding quality of uninterrupted energy delivery. ABB's integrated modular asset-management approach provides a clear picture of the risk structure and the maintenance required to deliver needed asset reliability and availability. This allows operation managers to make the best use of maintenance and replacement budgets, allocating funds to high-risk units.

By reducing the risk of failure within given financial constraints and by minimizing the impact of a failure when it does occur, ABB's TrafoAsset Management is providing a powerful service.

For more information on ABB's transformer offerings, please visit www.abb.com/transformers.

Thomas Westman
ABB Power Products
Zurich, Switzerland
thomas.westman@ch.abb.com

Pierre Lorin
ABB Power Products
Geneva, Switzerland
pierre.lorin@ch.abb.com

Paul A. Ammann
ABB Power Products
Baden, Switzerland
paul.a.ammann@ch.abb.com

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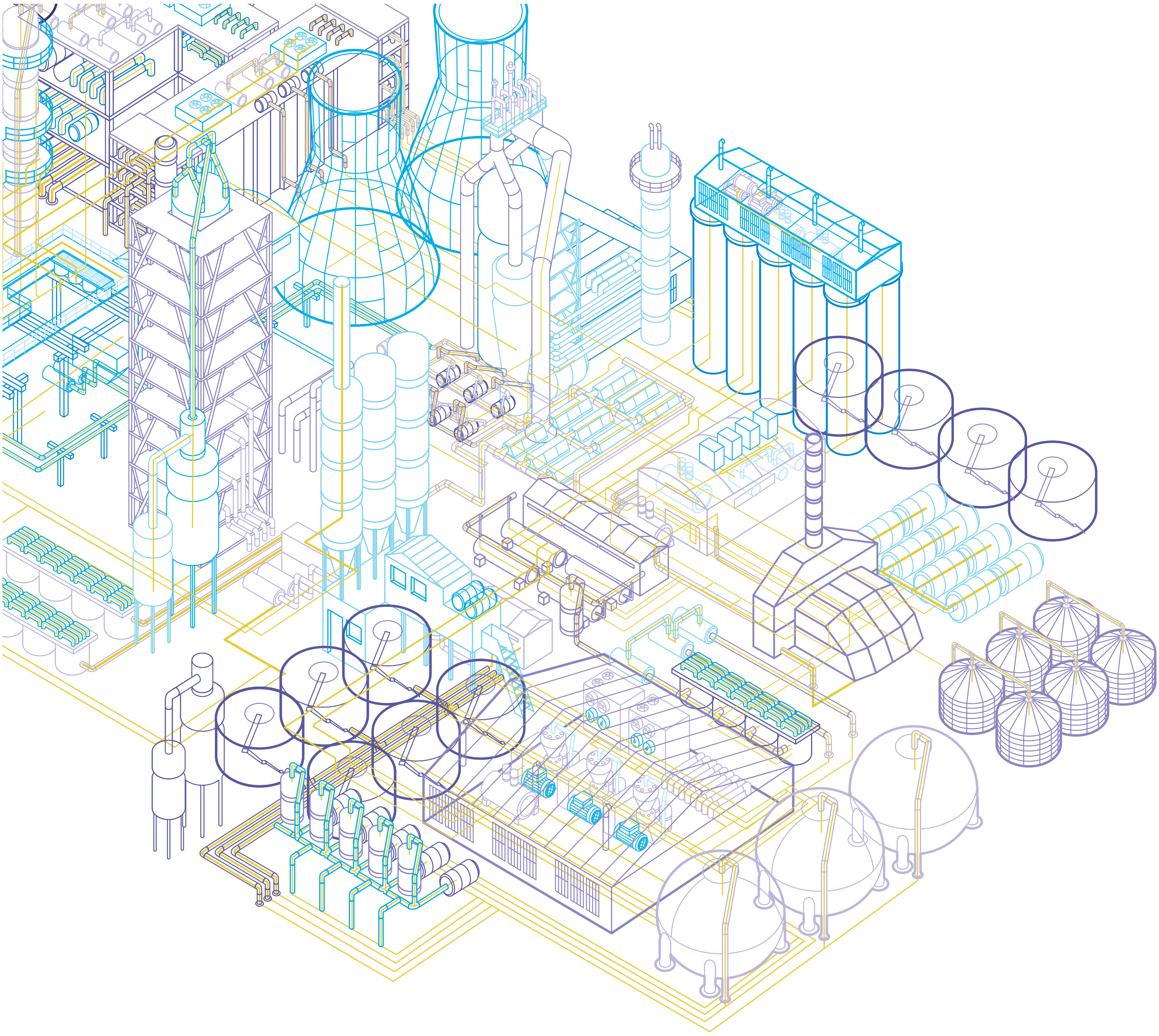


Hidden treasure

Drive data are a treasure trove of hidden information that can help industries solve problems before they even happen

MICHAL ORKISZ, MACIEJ WNEK, PIEDER JOERG – As processes become ever more complicated and margins thinner, minimizing downtime by ensuring that industrial machinery operates correctly is as important as ever. Proper condition monitoring of critical equipment can act as an early warning system against impending problems. However, condition monitoring is not used everywhere, often because of the expense of installing proper sensors and cabling, especially if the monitoring system needs to retrofitted to existing equipment. Another reason is that the task of selecting and interpreting the large quantities of data available in the most effective way seems daunting as well as costly. ABB has devised a way to easily access and process important data without the burden of additional equipment, costs and downtime. By extracting and processing data from existing devices traditionally used in process industries, such as drives, customers can prevent otherwise unforeseen problems from occurring and hence maximize the availability of their machines.

Industries are constantly under pressure to reduce costs while increasing service and productivity. The most effective way of fulfilling these aims is for managers to know the state of their equipment – in particular the critical components – at all times and to use this information to quickly identify and rectify faults before they spread to other parts of the process [1]. A good condition monitoring system helps predict the reliability of equipment and the risk of failure. With so much to gain, why is it that condition monitoring is not used everywhere? One reason is that existing equipment is often already retrofitted with a monitoring system and the installation of additional sensors and cabling could prove both complicated and expensive. Another reason concerns the interpretation of results. In many cases it may not be clear how to use a set of data that gives information about one aspect of a process to provide information about another. For example, determining the fractal dimension of a certain phenomenon may be fairly straightforward but relating it to the condition of a machine may not be so obvious.

Most processes use devices that are capable of collecting and producing relevant signals, which, if harvested and processed correctly, can also be used for diagnostic purposes. Among others, one such example is ABB's family of ACS variable-speed drives, which are often used to power critical equipment. The drives are based on powerful controllers that consume and provide tens, if not hundreds, of signals with sub-millisecond resolution.

To be useful for condition monitoring, data needs to be obtained from the drive inverter in one form or another. Internally the signals – which include measured and computed values such as speed, frequency, torque, flux, current, power and temperature, as well as parameters such as configurable drive settings – are stored in a regularly updated memory table. Data can be retrieved from this table as OPC [1] values or they can be loaded into hardware data loggers.

Data loggers are programmable buffers capable of storing values from several selected variables concurrently with a specified sampling rate, generally one that is high enough to make the data useful for spectral analysis. In normal operation, the newest data overwrites the oldest until the loggers are triggered by certain events, such as the occurrence of a fault or an alarm, a selected variable signal crossing a specified threshold or a software command. As the buffers are circular, some data prior to and after the trigger can be retained. ABB's DriveMonitor™ system → 1 can read the contents of a drive's hardware data logger. It consists of a hardware module in the form of an industrial PC and a software layer that automatically collects and analyzes drive signals and parameters [2].

Most processes use devices that are capable of collecting and producing relevant signals which can be used for diagnostic purposes.

Data enhancement

Because the resolution has already been determined and preprocessing has been performed, drive signals are generally available in a form not easily applicable to diagnostic evaluation. It is therefore necessary to employ a suite of "tricks" to transform the data so that it becomes useful for diagnostics.

True to their name, variable-speed drives dynamically change the frequency of the current supplied to the motor. The direct torque control (DTC) method employed in the drive produces a non-deterministic switching pattern, so there is no such thing as a constant switching frequency. This makes the straightforward application of spectral analysis methods somewhat challenging. Because individual spectra contain many hard-to-predict components collected one after another, the averaging of many spectra using point-by-point averaging, for example, is essential to obtain a "clean" spectrum.

In general, signals currently available from the ACS drive are used primarily for control purposes. Therefore some of the preprocessing needed for condition monitoring signals is missing. One such process is anti-aliasing filtering. Data points are sampled or computed at rates up to 40 kHz, but can only be accessed at lower rates (eg, by keeping every 40th data point). In signal processing it is typical that frequencies above the so-called Nyquist frequency – defined as half the sampling rate – should be filtered out prior to signal sampling. Skipping this step means the peaks from the higher frequencies will appear in the lower part of the spectrum, making it very hard to interpret. For example, signals containing frequencies of 400 Hz, 600 Hz,

1 ABB's DriveMonitor™

Footnote

1 OPC stands for object linking and embedding (OLE) for process control and represents an industry standard that specifies the communication of real-time data between devices from different manufacturers.

1.4 kHz and 1.6 kHz that are sampled at 1 kHz all produce the same aliased spectrum with a peak at 400 Hz.

When it comes to monitoring drive-induced changes in the output frequency, the high frequencies are important. Because they were not filtered out by the anti-aliasing filter combined with the fact that the drive's output frequency is rarely constant means they can be recovered.

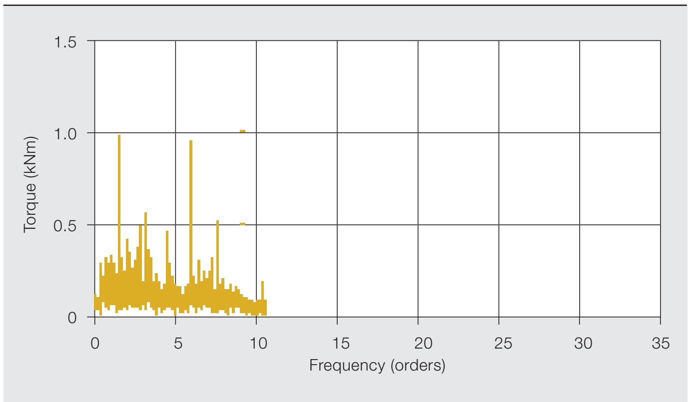
This recovery process is illustrated in → 2. The individual true spectrum containing the original and aliased peaks, as computed from the measured data, is shown in → 2a. The x-axis is scaled so that the output frequency is 1. This spectrum is "unfolded" by appending copies of itself (alternating between reversed and straight) along multiples of the Nyquist frequency. A number of unfolded spectra for varying output frequencies are then averaged so that previously aliased peaks are returned to their original place → 2b.

Variable-speed drives are generally used in applications where a process parameter needs to be controlled. The drive changes the output frequency in response to an external request (eg, to pump more water) or because of process changes (eg, more load on a conveyor belt increases the slip of an asynchronous motor) or perhaps because of a combination of both. While traditional spectral analysis methods assume constant frequency, frequency variations can be handled using one of two approaches: selecting constant frequency moments or rescaling the time axis.

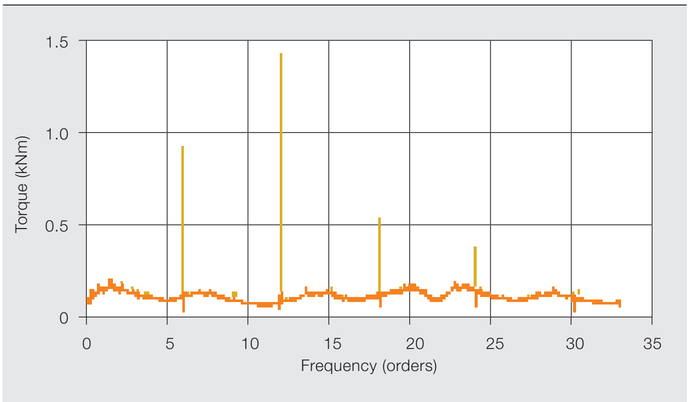
The first approach takes advantage of the fact that data is available in large quantities at any time. Most of it can actually be ignored in favor of keeping only a few "good" data sets. The trick, however, is knowing what to keep and what to throw away. A good criterion for selecting a suitable data set is that the output frequency should not change appreciably during the measurement, and only a set of conditions that occur regularly in the process should be considered for selection.

Sometimes the operating-point variations are so frequent that it is impossible to find such a stretch of data for any length of time. In such cases, the solution is to convert the data domain from time to another quantity, such as the electric field angle.[2] To aid in this transformation, various measurements can be collected from the drive inverter in parallel with the original signal. The instantaneous value of the output frequency[3] is one such measurement. This frequency is then integrated to yield the angle of the stator electric field, which then replaces the original x-value of each data point. Further normalization can be applied to the y-values.

2 An individual electric-torque spectrum



2a With aliased peaks



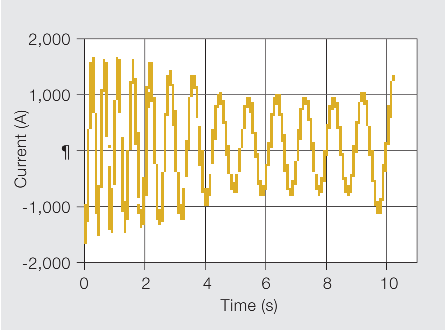
2b With an averaged "unfolded" spectrum

This transformation results in an x-axis that is no longer equispaced and therefore the fast fourier transform (FFT) spectral approach cannot be used. Instead, the Lomb periodogram method is employed [3]. This process, as applied to one of the phase currents of a hoist machine, is illustrated in → 3. The original signal with pronounced frequency and amplitude variability is shown in → 3a. The RMS current value reported by the inverter is given in → 3b and the measured instantaneous frequency is plotted in → 3c. The stator electric field angle is shown in → 3d and its shape follows the trend that the higher the frequency, the faster the rate the angle increases. The regular sinusoid shown by the solid mustard-colored waveform line in → 3e results when the original current signal is normalized (using point-by-point averaging) by the RMS current value and its x-axis respaced to reflect the angle. This in turn leads to a spectrum that is represented by a single-frequency peak (solid line in → 3f), while the raw data spectrum, shown by the dotted line, is not represented by a single-frequency peak.

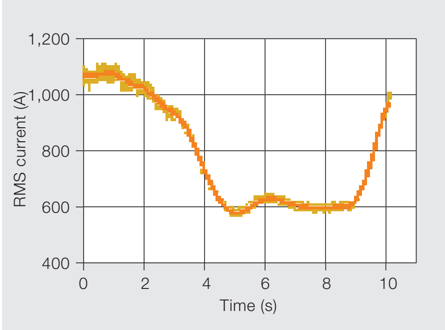
Different transformations can be applied depending on the information required.

The frequency variations associated with variable-speed drives can be handled by either selecting constant frequency moments or rescaling the time axis.

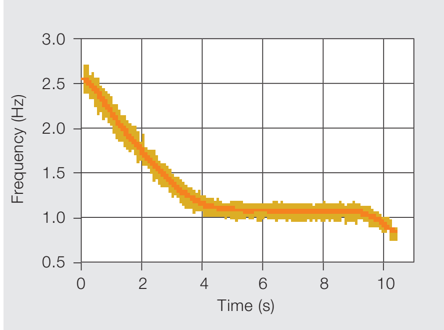
3 Normalization and transformation of variable frequency (and amplitude) current



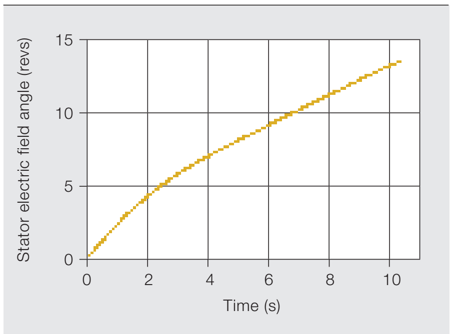
3a Original signal



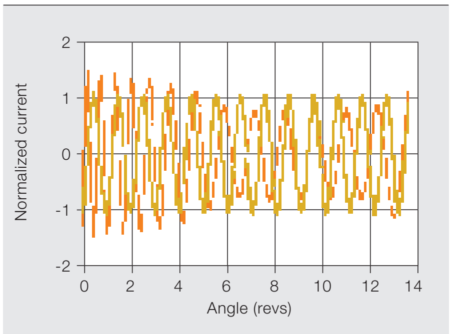
3b RMS current



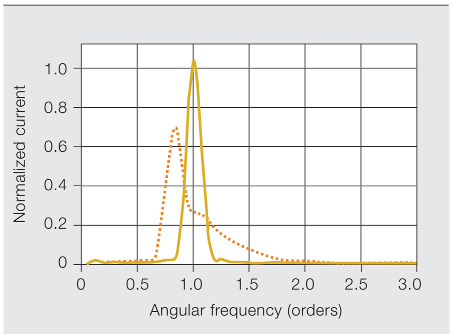
3c Instantaneous frequency



3d Integrated frequency (angle)



3e Transformed signal



3f Spectrum (raw signal is dotted; transformed is solid)

For example, suppose engineers want to know if certain motor defects such as imbalance, misalignment and bearing faults are present. Rather than measuring the instantaneous value of the output frequency, a motor speed signal may be acquired. After an analogous transformation, the x-axis represents the shaft angle, which in turn facilities the search for motor defects related to the rotating speed.

Diagnostic opportunities

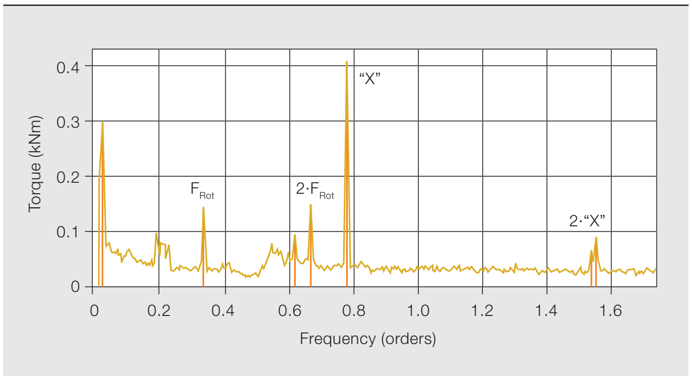
Converted drive data can be analyzed using two general methodologies that reveal different and important diagnostic information. These methodologies are:

- Point-to-point variability within one signal
- Signal-to-signal correlations

Point-to-point variability can be analyzed via spectral analysis in which periodic components are represented as peaks in the spectrum while various system defects or conditions can manifest themselves as spectral features with different frequencies. Signal-to-signal correlations, on the other hand, give information about the operating point and any associated anomalies.

Other methods use acquired knowledge about the normal behavior of a machine or process, and any observed deviations are immediately indicated. Irrespective of which method is used, their underlying purpose is more or less the same – to produce key performance indicators (KPIs) that give adequate information about, for example, the health of a machine, process robustness or supply quality. The conclusions can also be helpful in uncovering the root cause of a problem once it has been identified.

4 A fragment of the torque-signal spectrum from a rolling mill. On the horizontal axis, one equals the output frequency.



Spectral analysis

Drives equipped with an active rectifier unit can use the spectra of supply voltages and currents to yield valuable information about the quality of the power supply. Phase currents and voltages that are measured concurrently enable engineers to check for possible unbalances, phase shifts, harmonic distortions, etc. Similarly, looking at the harmonic content of the output current is a means of verifying the quality of the motor's power supply. The drive provides information relevant to the motor (such as frequency, torque, power, RMS current and flux) and to the inverter operation (such as internal DC voltage levels, speed error and switching frequency). In fact the spectral analysis of data supplied by a drive is capable of revealing more than is uncovered by the "classical" analysis of electrical or vibration signals.

An example of an averaged torque spectrum from a rolling mill is shown in → 4. The horizontal axis is scaled so that the output frequency equals 1. There are two peaks related to the rotating frequency, F_{Rot}. In addition, a family of peaks exists at an interharmonic frequency of "X" = 0.7742 (37.86 Hz) and 2"X" (1.5484), and

Footnotes

2 These domains are equivalent when the frequency is constant.

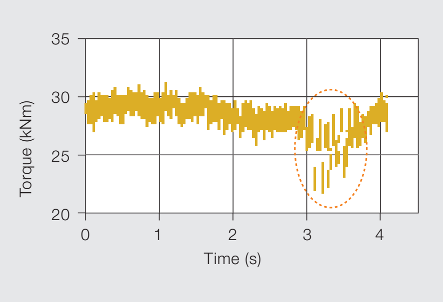
3 The frequency the drive establishes on the output current. The drive controls this frequency so it knows its exact value.

this likely corresponds to a resonance frequency in the driven equipment. This is an interesting piece of diagnostic information since such resonances accelerate equipment wear, which in turn could negatively impact certain process quality issues, such as the uniformity of rolled metal thickness.

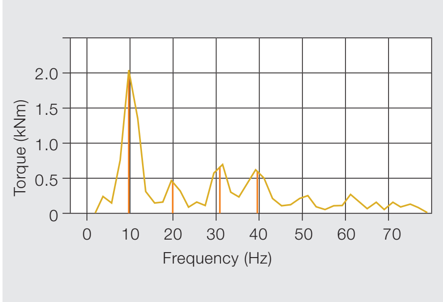
Transient phenomena

Spectral analysis also helps to reveal the presence of transient phenomena in drive data. As well as stationary oscillatory components in the signals, other more temporary events may also be present that are indicators of potential problems. For example, the raw torque signal from a rolling mill, measured over the course of 4s is shown in → 5a. Some form of ringing, which lasts roughly half a second, is evident after approximately 3s. The spectrum of this ringing fragment is given in → 5b where a 10 Hz frequency component and its harmonics are obvious. The source of this oscillation is unknown but the spectrum has highlighted a potential problem that needs to be investigated.

5 Transient phenomena in a torque signal.

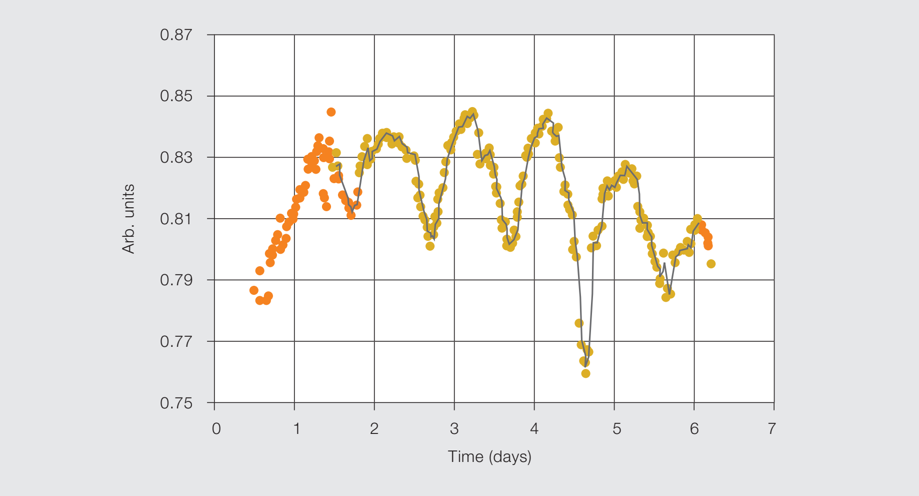


5a The raw waveform with ringing



5b Spectrum of the ringing fragment

6 Time evolution of the torque/speed ratio (τ/n2) for a fan



The spectral analysis of data from a drive is capable of revealing more than is uncovered by the "classical" analysis of electrical or vibration signals.

While it is impractical to continuously collect high-frequency data, the periodic collection and examination of such signals significantly improves the chance of detecting unwanted temporary occurrences.

Operating-point tracking

Concurrently tracking operating-point quantities (such as current, torque, speed, power and frequency) in drive data is an example of the signal-to-signal correlation methodology mentioned previously. Analyzing the relationships between certain quantities can shed light on both the operation of the machine and the state of the process. The relationship between torque and speed, governed by the fan laws, is a good example of a process-dependent relationship.

The velocity pressure difference at the output Δp is proportional to the gas density ρ and the square of the output velocity V:

$\Delta p = \rho \cdot V2/2$

Power P is equal to the pressure difference times the volumetric flow rate Q:

$P = \Delta p \cdot Q$

but it can also be expressed as a product of torque τ and rotating speed n:

$P = \tau \cdot n$

In normal operation under constant geometry, both Q and V are proportional to n, thus:

$\tau = C \cdot \rho \cdot n2$

where the constant C depends on the fan's geometry.

It follows that the ratio $\tau/n2$ reflects the density of the gas and the fan's geometry, which rarely changes.

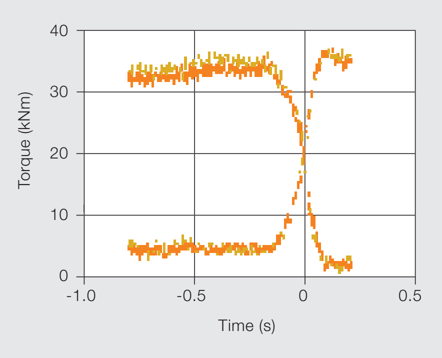
In → 6 this ratio for a drive-powered fan over a period of several days is plotted. The oscillations (with a period of one day) reflect the daily variations in temperature and thus the density of the pumped air. High density (cold temperature) occurs at night while low density (warmer temperature) is evident during the day. The drive data alone enables the evolution of process variables, such as inlet temperature, to be tracked. In addition, comparing this data with values from the control system (temperatures in this case) can lead to the detection of any unexpected discrepancies.

Tracking the operating point is possible without having to employ any additional hardware – the data is already available in the drive. The analyzed data can be presented directly or further analyzed by using the principal component analysis (PCA) technique described below.

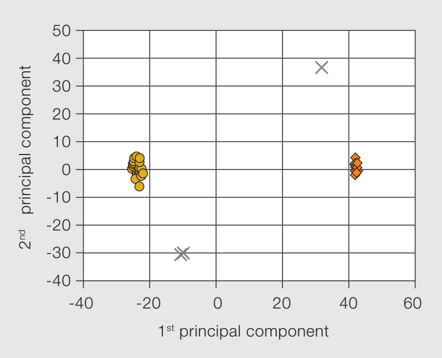
Cyclic process analysis

Some processes powered by a variable-speed drive are cyclic in nature. A rolling mill application is one such example where torque and current abruptly jump or increase as a slab is loaded onto the rolls and then suddenly decrease as the

7 A typical rolling mill torque profile



7a Examples of torque up and down profiles



7b The two clusters represent torque increases and decreases

ABB's medium-voltage AC drive ACS 1000

Drives are but one example of useful diagnostic data providers. Other examples include motor control centers, protection relays and intelligent fuses.

slab leaves. These jumps can be analyzed to detect any process instabilities or divergence from normal behavior that may be an indication of equipment wear or material variations.

In order to extract only the most essential information, high-resolution data gathered around torque jumps is processed using the PCA methodology [4]. This technique reduces multidimensional data sets to lower dimensions for analysis. These lower dimensions condense the set-to-set variability. Typical rolling mill torque profiles are shown in → 7. Each profile in → 7a, corresponding to one jump, is reduced to a single point as shown in → 7b. Jumps – or points – that tend to cluster within certain boundaries generally indicate the process is operating normally while those outside could signify a problem. The full data set can be saved for further examination at a later stage or, if the analysis takes place in real-time, more data can be collected.

Healthy machines, healthy processes

In today's competitive world, unplanned downtime can be disastrous for a company. That is why industries are constantly striving to maximize the availability of their machines. To do this effectively, some form of condition monitoring needs to be in place so that maintenance can be scheduled or actions taken to avoid the consequences of failure before it occurs. Condition monitoring is increasing in importance as engineering processes become more automated and manpower is reduced.

The benefits of condition monitoring need not come at the expense of having to install additional equipment. Often the data provided by devices for one purpose in a process can be used to satisfy another at no extra cost. As an important part of an industrial process, ABB drives have access to and generate large quantities of data, which, when properly processed, can be used for condition monitoring and diagnostics. Drives are but one example of useful diagnostic data providers. Other examples include motor control centers, protection relays and intelligent fuses. As well as being data providers, these devices are capable of using their onboard computational power for analyses.

Michal Orkisz
ABB Corporate Research
Krakow, Poland
michal.orkisz@pl.abb.com

Maciej Wnek
ABB Low Voltage Products
Turgi, Switzerland
maciej.wnek@ch.abb.com

Pieder Joerg
ABB Discrete Automation and Motion
Turgi, Switzerland
pieder.joerg@ch.abb.com

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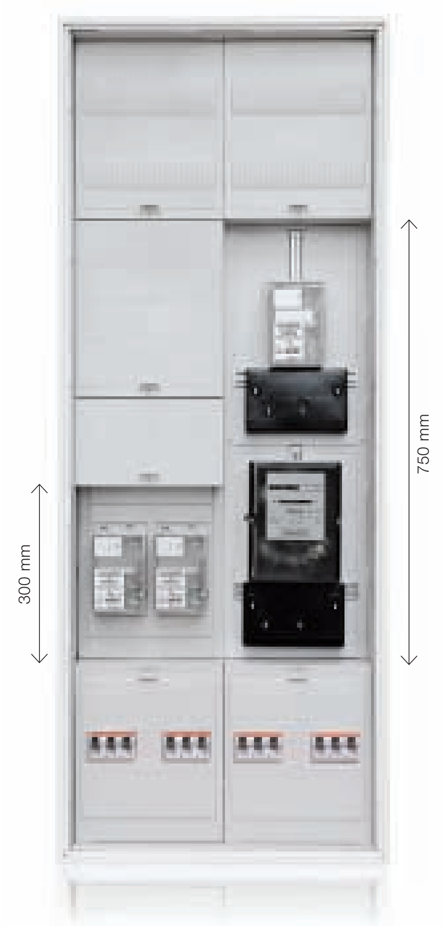
Smart metering

The meter cabinet as the metering and communication center

JÜRGEN LASCH – There are two main trends that are changing the way we, as consumers, look at energy. One of these is growing concern about the environment and especially the impact of energy usage. The other is the rise in energy costs, which is leading people to seek ways of consuming less. Both of these effects are changing the way people use energy. Despite good intentions, it is not always easy to link day-to-day actions with their actual energy impact and hence act accordingly. Energy bills are typically received on a monthly basis and it is difficult to distinguish the effects of individual actions or obtain meaningful feedback as to the effectiveness of changes.

1 ABB's electronic domestic supply meter (EDSM)

2 More functionality in less space



The introduction of so-called smart metering technology is changing this. At the Hanover Trade Fair 2009, ABB presented its electronic meters for domestic supply. In combination with a "data gateway," such a device enables customers to visualize and track their energy consumption and so identify ways to optimize it. Data is displayed graphically in a format that is simple to understand, enabling consumers to instantly optimize their energy use and immediately see the results of their actions – for example when they install an energy-efficient refrigerator.

The German Federal Government has made the introduction of smart meters mandatory in Germany from 2010. With the introduction of the electronic domestic supply meter (EDSM) → 1 and its integrated mounting and contact device (BKE-I), ABB is offering innovative aproaches to metering and distribution. The new technology makes it possible to build meter boards that are even more compact than the present ones → 2. Moreover, existing meter boards can be retrofitted with an adapter (BKE-A), easing the transition to EDSMs.

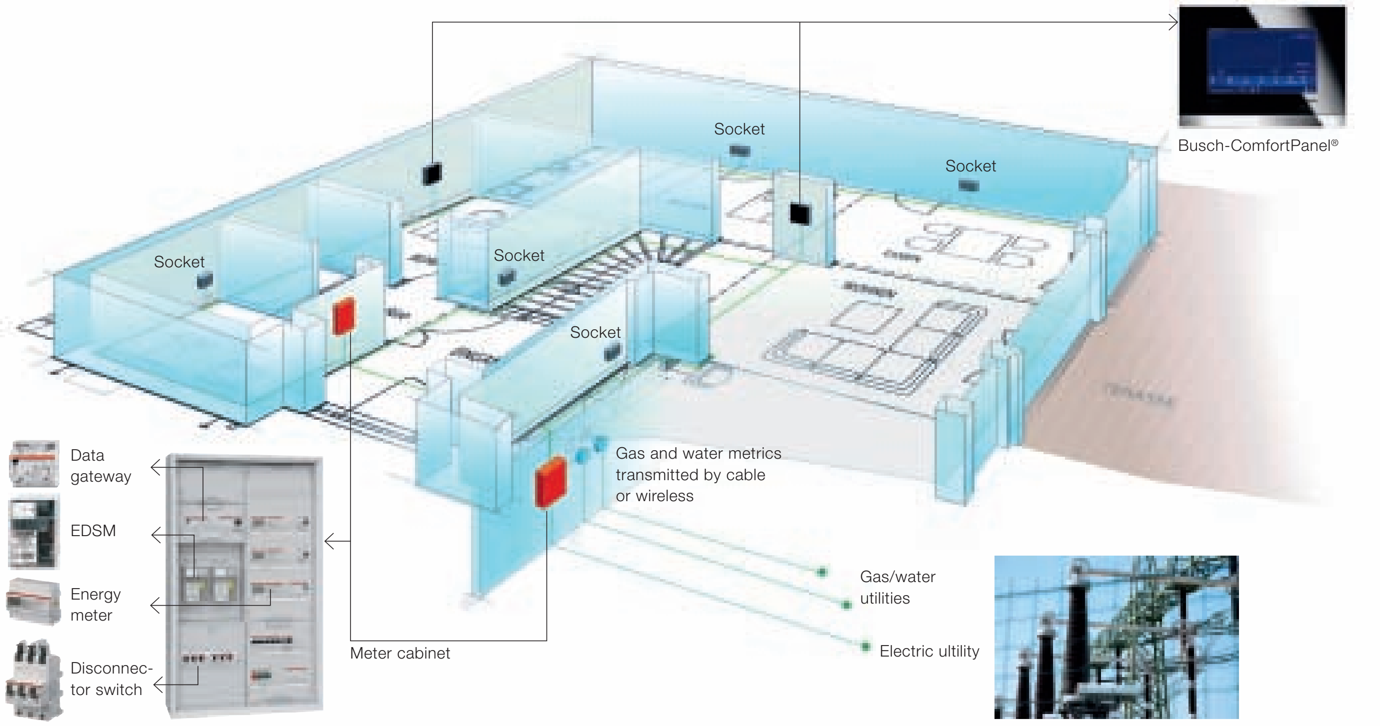
ABB's EDSMs are easy to install and set a new and forward-looking standard for domestic meters. They create a basis for smart metering and make it possible to not only use energy efficiently but also save money in a deregulated energy market. In combination with a data gateway → 3, they provide a complete solution for smart metering. Besides electricity, the gateway can monitor and visualize the consumption of other resources (such as water, gas or heat) and so represent an integrated and complete metering platform → 4. Data from the gateway can be presented to the building's residents in many different ways, for example on a PC, a mobile phone or a Busch-ComfortPanel® → 5. The data gateway also forwards this data to the suppliers. The additional devices needed for this are housed in the meter cabinet beside the smart electricity meter, thus turning this cabinet into a communication center.

Once such a meter is installed, the long-standing requirement for a utility employee to visit the site regularly and manually take a reading becomes history. The utility can periodically calculate consumption by remotely accessing the electronic meter. For the consumer, the energy consumption of the house is presented in an understandable format and at any time. Residents can thus influence their energy usage much earlier. Detailed analysis can even help reveal any damage to the network or hidden "power hogs."

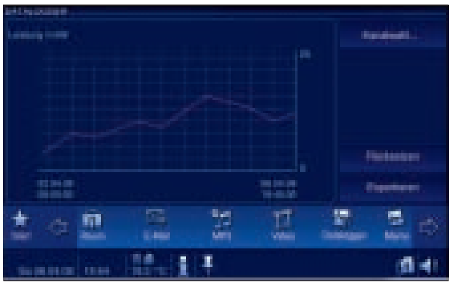
3 The data gateway

The energy consumption of the house is presented in an understandable format.

4 Smart metering



5 Consumption data display on a Busch-ComfortPanel



Electronic domestic supply meters (EDSMs)

EDSM facts for measuring active energy for meter reading purposes (billing) in single and dual-rate design:

- Designed according to VDN specification "Elektronische Haushaltszähler," Version 1.0.2
- Simple installation and replacement of meter
- Single or dual-rate meters
- With internal real-time clock
- Highly resistant to interference from magnetic fields
- Smart-metering ready

A more equal distribution of energy consumption can be achieved throughout the day and indeed the week.

Smart meters have an important part to play in a future in which consumers will have more freedom to chose their energy supplier. In a household equipped with a smart meter, power can be instantly and remotely shut off when an account is cancelled. Once the technology is ubiquitous, energy suppliers will increasingly offer time-dependent rates. Consumers will thus be encouraged to use high-energy appliances such as washing machines at low-rate times. In this way, a more equal distribution of energy consumption can be achieved throughout the day and indeed the week. This will lessen the need for costly peak load generation, and ultimately relieve energy suppliers by reducing the grid management workload that would otherwise be caused by increased use of renewable energies.

See also "The colors of intuition" on the following pages of this edition of *ABB Review*.

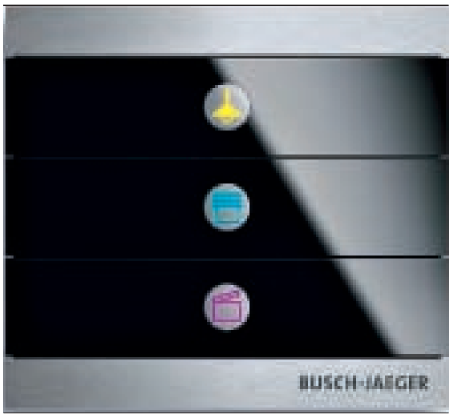
Jürgen Lasch
Striebel & John GmbH & Co. KG
A member of the ABB Group
Sasbach, Germany
juergen.lasch@de.abb.com

The colors of intuition

Innovative building- and room-control solutions win prestigious red-dot award

BERNHARD DÖRSTEL, PETER SIEGER – New technologies, while capable of making life better, can occasionally lead to frustration through their complexity. Developing a technology that is not only innovative but also intuitive can challenge even the brightest designers. In the area of building technology and room control, ABB has met that challenge: A part of the Busch-Jaeger Living Space concept, the Busch-ComfortPanel® (for building management) and Busch-priOn® (for room control) were jointly awarded the "red dot: best of the best 2008" prize for their intuitive user-control system. Busch-priOn is a modular control system for KNX-based building system technology. The concept enables the switching of lights, heating, air conditioning and home electronics from a single central position in a room that can also activate "living scenes" – preprogrammed settings that, eg, dim the lights, close the blinds and play one's favorite music all at the same time.

1 Triple control element of the Busch-priOn® control system



The backlit colored symbols identify the functional areas: lights (yellow), blinds (blue) and living scene (magenta).

2 The control system of the Living Space® solutions is complemented by easy-to-understand functional symbols.

The Busch-ComfortPanel® display

Increased functionality and ease of use are the qualities that set a new technology apart from the others. Busch-priOn is one such technology. Following the principle of "simplexity" – simple controllability and focus on the essential – the user can intuitively control even complex functions. This concept is based on the idea that any simplification is welcome in an ever more complicated world.

A multipurpose control unit

The Busch-priOn distributed room control unit bridges the gap between the company's classical switch program and modern panel solutions. It provides clear and intuitive control of building-system technology components such as illumination, heating, air conditioning and blinds. A central aspect of its comfortable use is the color-oriented control concept. And thanks to its modular structure, Busch-priOn can be individually adapted to the user's needs ➔ 1.

The availability of a wide variety of functions provides real freedom to customize individual needs. Lights, blinds, and consumer electronics can be controlled individually or integrated into complete "living scenes." This allows the desired backdrop to be created at the touch of a button: The light is dimmed, blinds are closed and one's favorite music is played.

During the customer-oriented development process of Busch-priOn and Busch-ComfortPanel, simplicity and ease of use were accorded top priority. In fact, the idea was that users would not need a manual to navigate through the panel's menu.

The central module consists of the Busch-priOn, a 9 cm (3.5 inch) high-resolution thin-film transistor (TFT) graphic display combined with a rotary control element. The touch-screen display features a circular menu with specially designed icons combined with clear text, showing the eight functional areas that can be selected with the rotary control element and activated with a push of a button ➔ 2. A ring-shaped, colored "aura" indicates at a glance which functional area is currently

Thanks to its modular structure, Busch-priOn can be individually adapted to the user's needs.

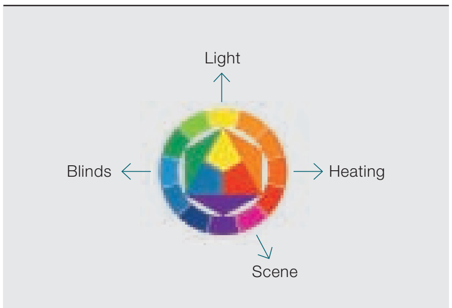
A red dot for Living Space

Busch-Jaeger's innovative Living Space platform also won the "red dot: communication design 2008" award. This virtual presentation platform allows intelligent building control technology to be explored interactively. Using a virtual house outfitted with Busch-Jaeger technologies, the user can experience the advantages of the products. The result is a sophisticated and aesthetic room reflecting the special brand and design philosophy of the company. This virtual solution and experience world was presented for the first time at the Light+Building 2008 fair in Frankfurt, Germany.

3 Winner of the "red dot: best of the best 2008" award

Busch-priOn, the modular room control unit for KNX-based building system technology. Functions can be easily selected with the rotary control element, whose colored aura indicates the chosen function (here, blue for blinds).

4 Busch-priOn's color-oriented user-control system utilizes four colors.



Each color – yellow, blue, amber and magenta – is logically assigned to a different functional area.

Busch-priOn uses state-of-the-art low-power processor technology and an advanced display with LED backlighting.

activated → 3. Three different screen representations are available, which can be selected according to the user's individual taste.

Using an additional device – the so-called media box – radio and video components can be controlled as well. With the Busch-ComfortPanel, the layout of a house, including the location of the controls, can be clearly depicted.

Each function can be quickly selected and controlled. Individual lamps can be controlled and dimmed directly. Shutters and blinds can also be operated with the rotary control element, and the temperature in the building can be set for each room using the individual-room temperature-control function.

The rotary control element of Busch-priOn can be combined with or extended to different modules. All control elements of the system, including the TFT display, feature a switch-selectable day and night illumination that allows the level of brightness to be adapted accordingly.

In addition, the control panel features rocker switches, which can be used to select freely programmable functions. When the panel is deactivated, it works like a regular switch triggering a predefined primary function when the rotary control element is touched.

Extra comfort and energy efficiency is provided by an optional infrared receiver and proximity sensor on the upper border strip of the Busch-priOn. This combines design and function in an intelligent way: When an occupant comes close, it automatically activates the background illumination of the room control unit. Similarly, the lower cover strip can be combined with a temperature sensor, so a room-temperature controller is possible.

The winning feature: color

Busch-priOn and Busch-ComfortPanel feature an intelligent, color-based user-

control concept that color-codes each functional area → 4. For example, all illumination functions are identified by the color yellow (symbolizing the sun and brightness), heating functions are marked amber (for warmth and comfort), the blind control is labeled in blue (symbolizing coolness and the color of the sky), and magenta – symbolizing extravagance, theater and staging – is used for light scenes. These codes are language independent and can be internationally understood. This feature can be complemented by easy-to-understand functional symbols, making any text labeling of the user interface unnecessary.

Busch-priOn and Busch-ComfortPanel feature a language-independent, color-based user-control concept that color-codes each functional area.

The elegant, flat design of the control panel matches any interior design style and is available in glossy white, glass white, glass black and stainless steel finish with a special anti-fingerprint coating.

The red-dot award

The innovative user-control concept of Busch-priOn received the prestigious "red dot: communication design 2008" award at the end of 2008. With more than 10,000 applications from 60 countries, the red-dot award is one of the largest design competitions worldwide, and is a coveted trophy as an internationally renowned symbol of design quality in three areas: product design, communication design and design concept. The world-renowned reputation of the award is ensured by a panel of judges consisting of internationally recognized designers and design experts from around the world.

Judges examined nearly 6,000 entries from 39 countries for the communication design award. Of these, only 38 submissions were awarded a "red dot: best of the best" prize for particularly excellent design achievements. The Busch-ComfortPanel and Busch-priOn were among the winners, receiving the award for their intuitive user-control system → 3.

The supporting technology

Busch-priOn is based on a modular, individually configurable support frame concept. A sub-bus system ensures an energy supply to the individual modules as well as the data communication between the modules. The system uses state-of-the-art low-power processor technology and an advanced display with LED backlighting.

Busch-priOn is suitable for private homes as well as for functional buildings. The fact that only a single flush-mounted box is needed for each configuration, no matter whether a single or combined unit is used, makes it particularly interesting for refurbishment projects. All units are compatible with ABB Powernet® EIB/KNX and ABB i-bus® EIB/KNX.

Electricians benefit from a fast and trouble-free commissioning of Busch-priOn. Not only is the programming procedure well known, the programming can also be stored on an SD card in the workshop and then transferred into the system on-site.

A device for efficiency

Busch-priOn is an advanced user-control device for building-system technology with an intuitive user-control concept and numerous customizable functionalities, boasting technical innovation, elegance and accessibility. And by carefully controlling the lights and heating, the device is helping to increase energy efficiency.

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Bernhard Dörstel
Busch-Jaeger Elektro GmbH
A member of the ABB Group
Lüdenscheid, Germany
bernhard.doerstel@de.abb.com

Peter Sieger
Sieger. Agency for Business Communication
Halver, Germany
sieger@buero-sieger.de

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Smart mobility

The present issue of *ABB Review* shows how ABB's innovations and technologies are permitting the generation, transmission and consumption of electric power to become more sustainable, flexible and reliable. ABB's involvement in transportation is not limited to the grid, however. The next issue of *ABB Review* will explore how the company is similarly bringing innovation to the movement of people and goods.

A large part of this issue will look at ABB's involvement in the rail sector. Although ABB is not itself a train manufacturer, the company supplies numerous vital components to the railway industry. These range from traction motors through traction transformers and converters to substations for the railway power supply. Beyond this, the company is also active on the service, maintenance and retrofit side of the rail business and so plays an important part in upholding the reliability of its customers' operations. *ABB Review* 2/2010 will look at some of the company's key technologies and the breakthroughs and show how they are revolutionizing rail travel across the world. The rail aspect will be rounded off by a history article celebrating some of the achievements and inventions of ABB and its predecessor companies from the early days of railway electrification to the present day.

Besides railways, *ABB Review* will also look at some of the company's other involvements in making transportation more sustainable. These range from a green breakthrough in the marine sector to recharging the batteries of electric cars.