



# ABB Review

The corporate technical journal  
of the ABB Group

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## Special Report Dancing with the Dragon

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**ABB**

# ABB Special Report Dancing with the Dragon

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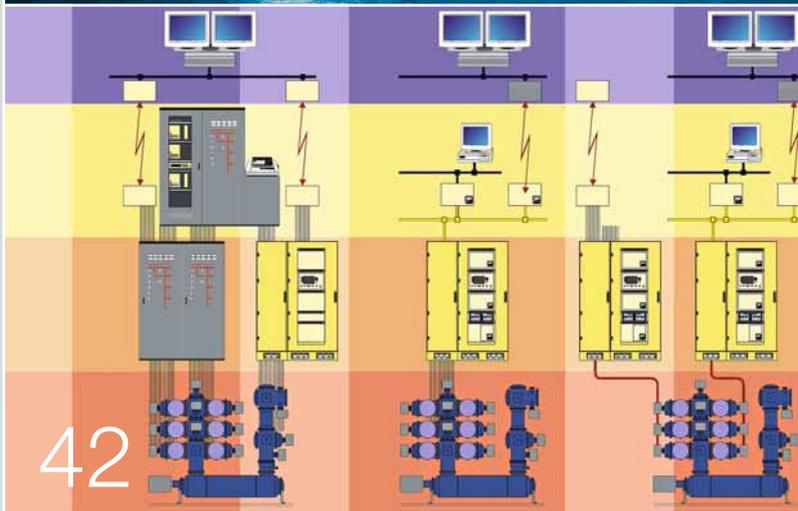
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## Dancing with the Dragon

On the list of countries in the world displaying a strong economic growth, China, for sure, has a prominent place. This culture going back thousands of years into history, with its extraordinary stream of past inventions that have influenced global technology, has in a very short period of time developed into a vibrant economy. Looking back at recent decades following its opening to the outside world, it seems as if the dragon, which contrary to Western mythology is in China a symbol of good fortune and creative power, has started to fly and is now inspiring the whole country and even the broader region to grow.

ABB is the leading power and automation technology group, with the ability to provide the products, systems and services the global economy urgently needs. Wherever electrical power is requested and wherever industrial production must be made extremely efficient, ABB delivers the required solutions and optimally serves its customers around the world. ABB's technologies, used by its numerous customers in China, help the Chinese dragon to dance with beautiful rhythm.

We at ABB feel like dancing with the dragon, because China, with its urgent and enormous need of electrical power and highly efficient production infrastructure, can, like many other countries in the world, benefit from ABB's long experience.

Already 101 years ago, ABB was helping the Chinese industry with the delivery of boilers. Today, China is one of ABB's major business partners.

ABB, active in more than 100 countries worldwide, has a huge portfolio of technologies that are highly relevant to the technological challenges facing China. However, the

products and systems developed by ABB in China contribute to technical solutions in other countries as well. The need to transport electricity with low losses over thousands of kilometers in China requires new approaches. The technologies thus developed will also be helpful in transmission systems in Europe or the United States where the reduction of losses is high on the agenda. Robot applications developed for specific production requirements in China will soon be seen in other factories around the world as well.

This bidirectional technology transfer is the foundation of a partnership that supports the dance with the dragon.

With this *ABB Review Special Report*, we want to give you a flavor of the technologies ABB can offer to its Chinese customers and demonstrate the ongoing successful applications in China that we achieve almost every day.

We also want to show how our research center in China and the engineers in our Chinese factories, together with their customers, contribute to the breathtaking growth of the technological competence of this huge country, a competence that radiates to the entire globe.

Enjoy your reading.

Brice Koch  
Chairman and President  
ABB (China) Ltd

Peter Terwiesch  
Chief Technology Officer  
ABB Ltd

# Flying with the dragon

ABB embraces a century of cooperation with China

ChunHua Lu



In 1907, the delivery of a steam boiler witnessed the first cooperation between ABB and China. A century later, the bilateral cooperation is reaching an unprecedented level. As an eyewitness, ABB has experienced a China rising up from isolation and poverty; as a participant, ABB has been proud of linking its name with many milestone projects in China; as a collaborator, ABB has become an integral part of China's economic and industrial development.

## ABB in China

Today, ABB has established a full range of business activities in China, including research and development, manufacturing, and sales and service, with one holding company, 26 joint ventures and wholly owned companies, and an extensive sales and service network across 60 cities. In 2007, total revenue and orders in China rose to \$3.4 billion and \$4.1 billion, respectively, and the number of employees in China also increased to 12,800, turning China into ABB's number-one market in terms of revenue, order and employment.

In 2008, ABB continued its rapid progress with its footprint strategy in China, speeding up the expansion of its existing factories in many cities, launching the ABB transformer design center in Chongqing <sup>1</sup>, and setting up a new joint-venture company of ABB Tianjin Switchgear Co, Ltd and Tianjin Binhai Huineng Investment Co, Ltd.

ABB China is not only the global basis of ABB's manufacturing and sourcing, but also is a great contributor of technology, talents and more to the ABB portfolio.

### Win-win cooperation

China, like a flying dragon, has injected strong power in the global economy, offering vast opportunities to such multinationals as ABB. And based on leading-edge products and technologies, ABB's business is flying with the giant dragon.

Facts speak for themselves: Since the first manufacturing joint venture was established in Xiamen, the number of employees at ABB China increased from 354 in 1992 to 12,800 in 2007, and the investment grew from \$10 million in 1992 to \$820 million in 2007.

ABB's localization process is accelerating. Currently, over 90 percent of ABB's businesses in China feature locally originated products and services, and 99 percent of ABB China's 13,000 employees are Chinese citizens. ABB China is also an exporter of product accessories, technical designs and services to 15 countries, including the United States, Germany, Switzerland and Sweden.

The number of employees at ABB China increased from 354 in 1992 to 12,800 in 2007, and the investment grew from \$10 million in 1992 to \$820 million in 2007.

The localization process is also being helped along by ABB's top executives. As active participants in the international advisory conferences held in Beijing, Shanghai, Chongqing and Guangdong, ABB leaders are contributing their expertise toward the local development in China.

### Economic success

China's economic success has been good not only for China, but also for ABB. For example, ABB Chongqing Transformer Co, Ltd is the first joint venture approved by China's central government to produce power transformers with a voltage of 500 kV. The local government helped make this venture possible by building a special heavy road from the company to the river port to facilitate the transportation of the massive transformer.

In response to China's "Go West" strategy, ABB made the single largest investment in Chongqing. Today, ABB has two joint ventures in Chongqing and Xi'an – two important cities in China's west – and has established numerous branch offices in the west, including Chengdu, Kunming and Hohhot.

With a commitment of long-term development in China, ABB has dedicated itself to helping the country achieve its goal of energy efficiency and environmental sustainability.

### Significant contributions

ABB is proud to have participated in many "power lines" in China, such as a major sports event in Beijing, the Three Gorges projects <sup>2</sup> and the south-to-north water diversion project.

#### Factbox Recent significant contracts in China

- Two \$70 million orders from State Grid, including HVDC transformers in 2008
- \$35 million order for Shanghai, Tianjin and Shenzhen metro projects in 2008
- \$28 million contract to provide propulsion systems for China's largest semi-submersible heavy-lift vessels in 2008
- \$29 million traction transformer contract on China Railway's hi-speed sleeper car EMU project in 2008
- \$440 million order for the 800 kV 6,400 MW UHVDC project, the longest power link (Sichuan to Shanghai) in the world in 2007
- \$56 million from Sha Steel Group in 2007, the largest metal order for ABB
- \$65 million order from Shanghai Zhenhua Port Machinery for automation and power systems for 74 shipping cranes at Asian ports in 2007

<sup>1</sup> ABB launches its transformer design center in Chongqing.



For the sports event, ABB provided its leading-edge products and technologies to over 30 projects, including stadia, utilities (eg, the new Chaoyang 500kV substation) and metro/airport infrastructure constructions, all of which significantly added value to the event's high-tech and green themes **3**.

Backed by ABB's world-leading technologies and global resources, the high-voltage direct current (HVDC) power link connecting Three Gorges to Changzhou, Guangdong and Shanghai was successfully launched, providing timely clean power to the power-hungry areas in China's east. The three HVDC power links built by ABB saved enough power for 500,000 households.

ABB was chosen to supply its world-class drive technologies to the south-to-north water diversion project. The gigantic project will help move 44.8 billion m<sup>3</sup> of water per year through three canals from the water-rich south to the drought-prone north in China.

In order to enable one million local residents to enjoy a comfortable room temperature above 18°C, even when the average outdoor temperature is -21°C, ABB completed one of the largest district heating projects in Daoli, Harbin, using recycled hot water from a local plant. The heating project helps eliminate 500,000 tons of greenhouse-gas emissions a year.

In 2008, ABB Beijing Drive Systems Co, Ltd completed its third expansion,

doubling the production capacity to meet the demands for energy-efficient drive products in China. Since its establishment, its drives have saved a total of 35 billion kWh of power for customers in China, enough to meet the needs of all the households in China's four municipalities – Beijing, Tianjin, Shanghai and Chongqing – for one year.

In Shanghai, ABB's tailor-made automation systems have helped the Luoqing Port to become the world's first automated bulk-cargo wharf to achieve a throughput of 37.8 million tons of cargo annually.

Currently, China's rail network constructions are entering into a booming period. ABB has provided various solutions to many key rail-transport projects in Guangzhou, Beijing, Shenzhen, Shanghai and Tianjin, all of which have good safety records.

ABB's contributions will go on, and the company has been steadily transferring more businesses and technologies to China. As a result, ABB has earned a number of significant contracts **Factbox**.

#### Research and development in China

Research and development is vital for ABB's technology leadership. In March 2005, ABB opened a new Corporate Research Center in Beijing with a branch in Shanghai, a concrete step to understand, foresee and support China's future in the power and automation industry. As an integral part of the ABB global research network, the

center in China focuses on power transmission and distribution, manufacturing and robotics.

ABB has also established research teams in each business division in China to maintain its leading position in the market. The ABB China High Voltage Technology Center is one of them, and was established in September 2007 in Beijing. The center aims to bring breakthrough technologies to the Chinese market and to contribute to global technology developments. The team is developing live and dead tank breakers, gas-insulated switchgears, instrument transformers, capacitors, surge arresters and accessories for cables.

In addition, each local ABB company in China has a technical team to cater to the needs of local markets. In 2008, the ABB Global Transformer Design Center was established in Chongqing, which turned ABB Chongqing Transformer Co, Ltd into a full-fledged global transformer base, combining design, manufacturing, engineering service and insulation-material supply. In fact, the center has also designed transformers for ABB customers in countries such as Sweden, Germany and the United States.

ABB accelerated its localization process by transferring technologies to China to reinforce local research and development as well as manufacturing capabilities. In early 2006, ABB relocated the headquarters of its global robotics business to Shanghai. In 2007, ABB's latest type of robot was

**2** Three Gorges Dam



**3** ABB's people power contributes to its success.



## ABB in China

introduced into “local manufacture” in China, producing heavy industrial robots and controllers.

ABB drives have saved a total of 35 billion kWh of power for customers in China, enough to meet the needs of all the households in China’s four municipalities for one year.

Extraordinary capabilities have been displayed with the expansion of the research and development team in China. In 2007, for example, ABB Xiamen Switchgear Co, Ltd completed the grid power expansion project for the Guangzhou 110 kV Jiangnan sub-station with an innovative solution. The company’s service team took full advantage of the modular design characteristics of ABB’s MV switchgears to meet the requirements for the electricity capacity expansion and automation upgrading. By replacing some particular components, it enables successful upgrading of the whole system and helps customers save over \$700,000 and reduce the project throughput time to four weeks.

Another example of the contributions of the research and development group in China can be found in the textile industry. ABB Beijing Drive Systems Co, Ltd has developed application software for textile machinery, an entirely new technology in the textile industry that has brought op-



portunities for the industry to improve energy efficiency.

ABB has maintained a strong investment in research and development, even during difficult times. This commitment is helping the company keep its competitive edge in three key areas: energy efficiency, grid reliability and industrial productivity.

### Upstanding local citizen

ABB strives to be a good corporate citizen in China by enthusiastically assuming social responsibility. Support takes a variety of forms, and ABB runs a wide variety of programs, including supporting education, environmental protection, charity and common wealth.

As talents are one of ABB’s greatest assets, ABB attaches much importance to education. ABB provided scholarship and other assistance to talented but needy university students in China to fulfill their dreams; the company cooperated with vocational schools in Xiamen and Chongqing to set up “ABB Class” to help skilled young workers develop; and ABB also donated money to rebuild Nanye primary school in China’s north province of Shanxi.

ABB also aims to build a better world by supporting various kinds of environmental protection campaigns. ABB joined hands with a key customer – Inner Mongolia Power Company – to fight against desertification in Ordos, a city in China’s north Inner Mongolia Autonomous Region.

4 ABB engineers repair damaged HV breakers at Mianyang Power Supply after the massive Wenchuan earthquake in Sichuan.



As a responsible multinational, ABB is dedicated to making sustainable contributions to the communities where it operates. ABB stood beside its Chinese customers in recovering from disaster – in 2008, ABB offered various forms of timely assistance, such as donations and on-site service, to help customers to walk out of severe snow storms and a massive earthquake 4.

In addition, ABB has raised about \$150,000 for a project to improve the housing conditions of 1,000 elderly people in Shanghai. ABB employees in China as well have made charitable contributions to their community: ABB employees in Xiamen participated in the “Water of Life” campaign; ABB employees also took part in the Shanghai Special Olympics to provide necessary support to disabled sportspeople.

A century has passed, and the win-win cooperation between China and ABB will enter into another century, and beyond.

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# Power and productivity

China's challenges

Friedrich Pinnekamp, Isabelle-WenHui Liu

With more than 1.3 billion people, China is the largest country in the world today, being home for 20 percent of the world's population. As a consequence of that China is emerging as one of the largest global energy consumers, second only to the United States. Since 1980, rapid economic growth has stimulated an equally remarkable growth in energy production and consumption. China's demand for primary energy is likely to more than double between today and 2030.

A country with such strong growth needs energy to increase its standard of living and its industrial productivity if the consumption of goods and supply to the infrastructure are to contribute to the country's prosperity.

## ABB in China

The Chinese power industry is struggling to satisfying demand – growth in energy demand has out-paced supply growth. This represents a shift compared to the late 1990s, when problems were with oversupply. China's rapid development, changing demographics and economic restructuring have driven a relentless growth in energy consumption and present new challenges for power suppliers.

China's main source of energy by far is coal. Such heavy reliance on a "dirty" source has been costly; the government is planning to diversify the industry through increased use of cleaner sources such as nuclear, hydroelectric and natural gas. China is rich in many of the resources needed for energy production, but the regions where these are concentrated are far away from the main centers of consumption. The further growth of industry and commerce thus calls for heavy investment in both generation and transmission infrastructure.

The government is committed to such goals as diversifying energy sources, improving efficiency, expanding coverage and limiting the human and environmental costs of the rapid growth.

#### Energy demand: trends and forecasts

Since the late 1990s, when oversupply in the energy industry led to a moratorium on the approval of new coal-fired plants, supply and demand have shifted radically.

During the summers of 2003 and 2004, supply shortages led to about two thirds of Chinese provinces imposing brownouts and rationing ener-

gy. Electricity production has then been increased with highest pace <sup>1</sup>. The Energy Information Administration (EIA) predicts that Chinese electricity consumption will grow twice as fast as the world average in the years to come until 2030<sup>1)</sup>.

### The further growth of industry and commerce calls for heavy investment in both generation and transmission infrastructure.

This rapid growth is positioning China among the giants in energy consumption – a trend that will continue for the next five, 10 or even 20 years.

#### What is driving energy demand?

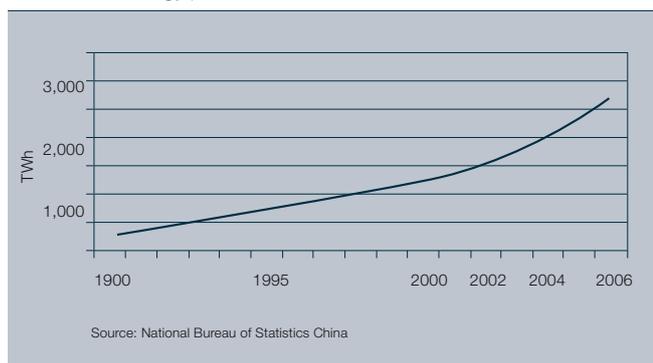
Increasing living standards, especially in eastern China, have substantially changed consumption patterns to include modern goods and services. This, combined with China's position in global export manufacturing, have in turn created opportunities of which the most important is rapid industrial growth – around 10 percent a year since 1980. Over the last years in particular, following heavy focus on areas such as construction and infrastructure, industrial energy demand has been very high. The scale of fixed asset investment in buildings, roads and factories has been huge in the last few years, and is by nature highly

energy-intensive. The construction boom and – by international standards – still low energy efficiency in China explain the scale of the energy demand increase.

Though industrial consumption accounts for roughly two-thirds of the growing energy needs in China, domestic consumption is also an important force to consider. This has grown steadily, a trend that is likely to continue through the coming decades. The rise of the middle class in China is starting to impact energy needs. As China becomes increasingly wealthy, factors such as demand for cars and more electricity in bigger houses will continue to increase. Likewise, oil and electricity demand will rise. Urbanization also has a huge role to play in this equation <sup>2</sup>. Only 42 percent of the Chinese population currently lives in urban areas, which is well under the global average of about 50 percent and far below the developed world average of over 70 percent. As the country develops, this balance is likely to shift towards heavier urbanization.

In China, there are significant differences between urban and rural energy consumption. Presently rural residents use below 40 percent of that of their city-dwelling counterparts. Due to high costs and poor access to commercial energy, this population currently supplements its commercial consumption with biomass and direct coal burning. If this inefficient and polluting non-commercial energy use is included in the energy balance, rural residents are using one-third more energy than their urban peers. In order to cut back on the current

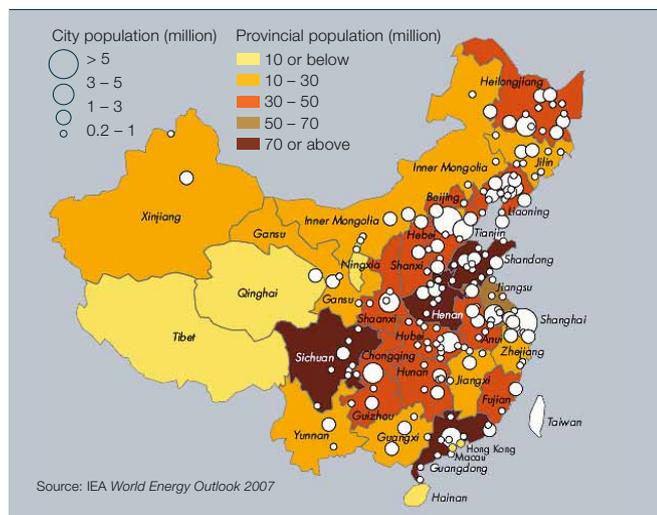
<sup>1</sup> Electrical energy production in China



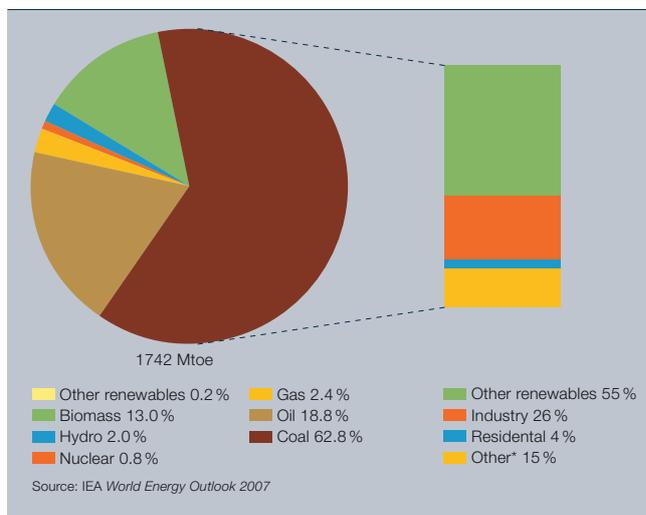
#### Footnote

<sup>1)</sup> Most of the data reported here are taken from the IEA *World Energy Outlook 2007* with a special emphasis on China.

2 Major cities in China



3 Primary energy demand in China



waste, pollution and health hazards of biomass and coal burning, rural provision of commercial energy is a government target. Growing urbanization will also contribute to this shift. The scale of the Chinese population means that changing demographics such as urbanization, rural electrification, and rise of the middle class are likely to have a huge impact on the Chinese and global energy market.

Demand-side changes are being facilitated through fundamental shifts in the energy supply. Rising energy needs are being accommodated through a variety of government efforts and private-sector developments.

### Energy efficiency

Among those efforts energy efficiency has attained even greater prominence over the past few years as the main approach to addressing energy security and environmental issues at the same time. Already in 1998, the Energy Conservation Law for more efficient use of energy resources and the promotion of energy-saving technology was launched. In 2004, Medium and Long Term Plan for Energy Conservation with specific energy efficiency improvement targets for the industrial, transport and building sectors came into place. These and other initiatives shall give guidance on technical measures to achieve the 20 percent reduction of energy intensity targeted for 2010, which is a feature of the 11<sup>th</sup> Five-Year Plan for energy. The subsequent national programs are strongly

driven by politicians who strive for a consequent implementation.

### From coal to “clean” energy

The primary source of Chinese energy is coal **3**. China possesses vast coal reserves and is both the largest producer and consumer of coal in the world. The government is working to decrease this heavy reliance on coal relative to other fuels, but coal will continue to grow in absolute terms and will definitely remain the country's largest energy source through 2025. The 11<sup>th</sup> Five-Year Plan seeks to increase the coal contribution in the energy mix to 66 percent from 63 percent in 2005.

### China possesses vast coal reserves and is both the largest producer and consumer of coal.

The coal resources in China are huge and distributed across the country **4**. In the coastal regions, however, where the electrical energy demand is highest, less coal is available. As a consequence, long transmission lines for electrical power are required to connect the power plants in the West with the centers of energy consumption in the East.

Oil is the next biggest source. During the 1990s, oil production in China doubled but still failed to keep up with rising demand – currently the

fastest in the world. China has been a net oil importer for the past decade.

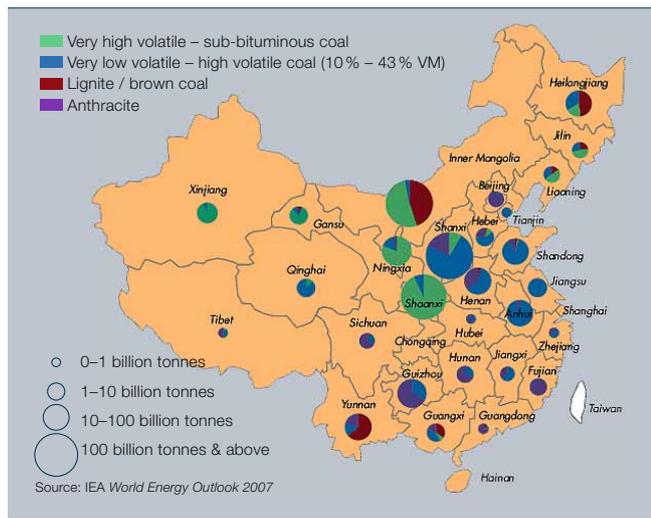
It is forecast the country will import 84 percent of its needs by 2030.

The next most important source of energy for China is hydroelectric generation. China possesses the largest hydroelectric resources in the world. This is a significant source of energy generation and will reach almost 7 percent according to the 11<sup>th</sup> Five-Year Plan. The Three Gorges project is probably the best known of China's endeavors to develop its hydroelectric resources. This 18,200 MW facility is meant to be completed by 2009 with a capacity to single-handedly supply 3 percent of current demand. Beside the Three Gorges, there are 25 smaller projects underway along the Yellow River (15,800 MW) and a 5,400 MW plant on the Hongshu River. Construction has also started on a 14,000 MW development at Xiluodu and 6,000 MW at Xiangjiaba.

Natural gas is currently a very small power source. Both western China and neighboring countries, such as Russia, possess substantial natural gas reserves. Gas from areas such as Xinjiang as well as imports will see increasing use in power generation. One clear advantage of natural gas is that it burns much more cleanly than coal. As part of Beijing's preparations for its “green” Olympics this year, a substantial part of the city's power supply has been switched to natural gas.

## ABB in China

4 Coal resources in China



5 Nuclear power plants in China



Nuclear energy, like natural gas, constitutes only a small fraction of present energy generation, but will expand at a furious pace in the coming years [5]. Mainland China has 11 nuclear power reactors in commercial operation, six under construction, and several more about to start construction. Additional reactors are planned, including some of the world's most advanced, to give a six-fold increase in nuclear capacity to at least 50 GWe or possibly even 60 GWe by 2020 and then a further three- to four-fold increase to 120 to 160 GWe by 2030. The 11<sup>th</sup> Five-Year Plan has targeted an overall contribution of about 1 percent to the energy mix.

#### Moving the energy: power grids

China's vast energy resources are predominantly concentrated in areas far away from the booming coastal and southeastern cities where consumption is greatest. One of the problems with the current system is that it is regionally focused and has insufficient interconnection. The government is planning to establish a unified national power grid by 2020, selling power at market-determined rates. This is a major factor in the efforts to better match energy supply and demand in China. One key part of this plan is the "West to East Plan," with major lines in the North, Center and South connecting the production of the resource-rich West to the needs of the energy-hungry East. The 2020 strategy also envisages connections to Russia in the north and Thailand in the south.

#### Health and the environment

The Chinese government is very well aware of the serious environmental issues connected to the required energy system. These issues identify air, water and ground pollution due to production, transformation, transportation and burning of fossil fuels. All potential negative effects also recognized in other countries like waste disposal, greenhouse gas emission, changes in ecosystems caused by large hydro-projects, to mention a few, are carefully considered.

Air pollution remains a major problem in China and the efforts of the government are manifold; for example:

- Factories have moved to less populated areas.
- Fuel has been switched from coal to gas where possible.
- Some large projects not complying with environmental requirements have been stopped.
- New emission standards for vehicles have been introduced.

Emissions of critical pollutants like SO<sub>2</sub> shall fall by 10 percent below the 2005 level by 2010.

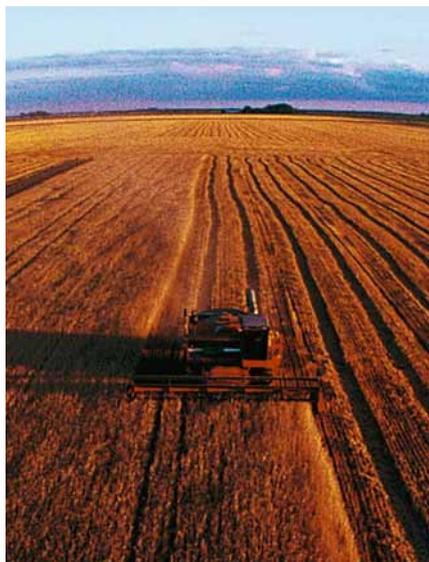
Renewable or CO<sub>2</sub> free energy resources have a high priority but will stay on a low percentage level for a long time. Hydropower still is the biggest alternative and there are plans to increase the capacity to about 300 GW by 2020. Hydropower of this large scale must overcome a number of difficult barriers, however.

China has installed a National Climate Change Coordination Office already in 1998, and in 2007, it released its first action plan to mitigate climate change, with a number of initiatives headed by the Premier.

#### Industrial productivity

In the last 10 years the major source of China's growth has been its industrial productivity [6]. Rapidly increasing consumption opens opportunities in the process and manufacturing industry to supply required products and services. Improving living standards demand better housing and transportation, better working conditions and a safer environment. Modern production technologies in combination with energy efficient equipment will enhance productivity, improve product quality and reduce energy demand per ton produced. These measures are all necessary in China's attempt to balance its growing demand with its capability to supply energy in the form of heat and electricity.

The leading sector in energy consumption is industry, representing 68 percent of total energy consumption. It is followed by the residential and commercial sector with a share of 11 percent, and transportation at 8 percent. It is expected that the industrial sector will continue to dominate energy consumption, though there will be a trend of rising transportation and residential sector share by 2020.



The major energy consumption subsectors in the industrial sector are chemicals (including petrochemicals) at 24 percent, metals (including smelting and pressing) at 20 percent and non-metals (including cement, paper and pulp; food; and textile) at 20 percent. The fertilizer, iron and steel, and cement industries are the major users in each of the three largest industrial subsectors.

#### China's fertilizer industry

China's largest industrial subsector from the energy consumption point of view is the chemicals industry with fertilizer production being the largest energy user within this subsector.

China's low production efficiency for fertilizers is due to almost 1,000 small plants and the use of coal as feedstock for its ammonia synthesis. Whereas the feedstock used in the United States is almost exclusively natural gas, coal is the main choice in China. The energy intensity for ammonia production is about 25 percent higher in China, a significant potential for energy savings.

#### China's iron and steel industry

The iron and steel industry accounts for 28 percent of total industrial fuel use. China is currently the world's largest producer of steel with about 500 million tons in 2007, being 34 percent of the world's steel production.

The energy required to produce the steel is comparably higher than in



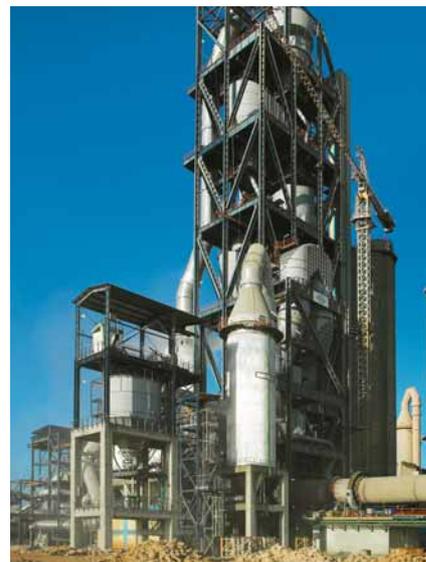
other countries, however. Some of the reasons are that the production capacity per blast furnace is small, the continuous casting rate is low and the iron-to-steel ratio is high.

China's vast energy resources are predominately concentrated in areas far away from the booming coastal and southeastern cities where consumption is greatest.

There are currently 6,686 steel companies in China, 58 percent of which are located in the coastal region. A consolidation process is driven by the government, however, so that in 2010 the top 10 steel companies should produce more than 50 percent of the national output. Just recently plans were launched to build a huge steel plant for up to 30 million tons of annual production near Fangchenggang, a port city in the Guangxi region in China's south with an investment of \$30 billion.

#### China's cement industry

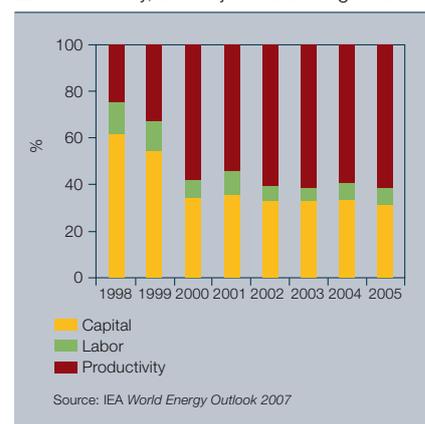
As the world's largest cement producer, with a share of around 40 percent, China has ranked first in terms of cement production for many years. The total cement consumption in China was 1.2 billion tons in 2006, up 14 percent almost every year; the cement output maintained the rapid



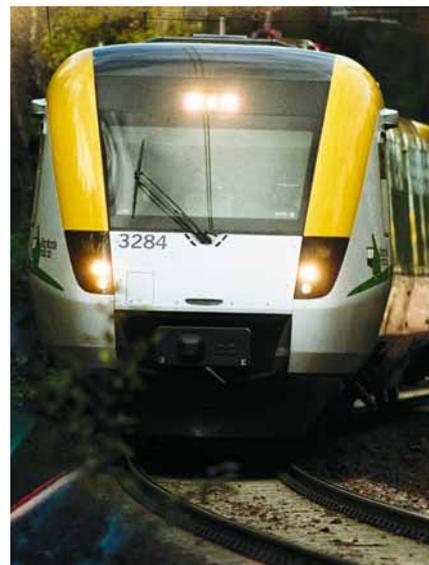
growth to 1.2 billion tons, increasing 15 percent. It was the strong demand in the cement market that cement industry recovered the prosperity in 2006. The industry has benefited from the growth in real estate and the rapid growth of the national economy.

However, the majority of China's cement producers are small plants using an inefficient process of vertical kilns – despite the Chinese government dramatically reducing the number of cement producers in the past. Only in 2020 are larger dry kilns expected to reach a share of 40 percent. No wonder the cement industry consumes around 77 percent of the energy in the non-metals sector. Energy still accounts for about 40 percent of the total production costs in this industry – a dramatic indicator of the industry's improvement potential.

6 Productivity, the major source of growth



## ABB in China



The demand for cement is expected to continue growing as China implements its strategies of developing the Western regions; reinvigorating the traditional industrial bases in north-east China, its urbanization drive and its projects for transporting natural gas from the Western regions to the Eastern ones; and projects related to a major international sporting event and the 2010 Shanghai World Expo.

#### China's pulp & paper industry

China's paper industry has experienced dramatic growth with consumption increasing by 45 million tons in 20 years to more than 60 million tons in 2006. China has become the second largest paper consumer in the world, only behind the United States, and is the world's largest paper importer with annual imports exceeding USD 7 billion.

There are several thousand paper and board companies in China, but only a handful of them have a capacity exceeding 200,000 tons per year. Some of the most modern mills in the world are operating in China today.

China's paper-making industry has experienced a rapid growth in consumption as well as in output; therefore, many leading Chinese paper-making enterprises started introducing new production lines, which resulted in an over expansion in production capacity, particularly in 2005 and 2006. In addition, the international paper-making giants have landed in China for investment and setup plants. China will

continue to expand its domestic paper production capacity and try to reduce its imports of paper. However, the country suffers from a shortage of pulp and pulp imports are expected to increase to 10 million tons by 2010.

### In the last 10 years the major source of China's growth is its industrial productivity.

#### China's automotive industry

China's automotive industry has experienced a high growth period as well. The number of vehicles has increased by almost a factor of seven since 1990, from 5.5 million to around 37 million in 2006. Most of this growth is in cars. China overtook Germany in 2004 and Japan in 2006 and became the second-largest car manufacturer in the world. The step to number one, producing more than the United States is expected around 2015. The IEA projects the number of vehicles on Chinese roads to exceed 270 million by 2030. China is likely to become an exporter of cars, in line with the developments the world has witnessed in South Korea and Japan in the past.

#### Transportation sector

The total energy consumption for China's transportation sector amounted to 130 million tonnes of oil equivalents (toe) in 2006, about 8 percent of the country's total. It is estimated that the transportation sector will take a

larger share of final energy consumption in the future due to the high growth of transportation services. Total energy demand for the transportation sector is estimated to reach 240 million tonnes in 2015 and 460 million tonnes in 2030.

#### China's harbors

The harbor industry has achieved fast growth with annual growth rates of 16 percent from 1999 to 2003. China's total trade of goods has surpassed \$ 2 trillion in 2007, with double-digit growth over the last years. Total seaborne port handling capacity has reached 5 billion tons. The large container facility in Shanghai is going to be the number-one container harbor after Singapore, and seven out of the 20 world's largest facilities are in China. China is becoming the biggest shipping center in the world.

#### The need for power and productivity

Economic growth is predicted to remain high for decades to come, which in turn means that the energy sector will continue to expand. Given the scale of the Chinese energy industry and its growth, efficiency in power generation and consumption is too low and environmental and health costs too high. The stakes are very large, but efforts by the central government to guide the energy industry's development are headed in the right direction. Diversifying energy sources, raising production standards, moving towards market-based prices, and improving interregional connectivity will

all help facilitate the healthy development of the Chinese energy industry.

Also in the foreseeable future the industrial sector will remain the largest energy consumer with residential and transportation rapidly increasing. There will be high demand to develop the energy supply infrastructure in the next 10 years. Coal will remain the dominant energy source followed by oil and natural gas.

The energy industry faces many challenges; some of these include: Energy supply resources are located far from the major demand centers. The largest and fastest growing indus-

trial centers are in the most developed eastern and southeastern areas. The transportation and transmission of energy will present a major bottleneck.

Industries must improve their energy consumption efficiency and move towards best-in-class productivity performance. This requires introduction and wide use of state-of-art technology in production and management.

All industries must make major efforts to reduce environmental pollution and focus on environmental protection.

ABB, with its broad portfolio of products, systems and services to support

utilities and industrial production, is best positioned to help Chinese customers in their challenging tasks.

This article is based on contributions in *ABB Review Special Report China* (2005).

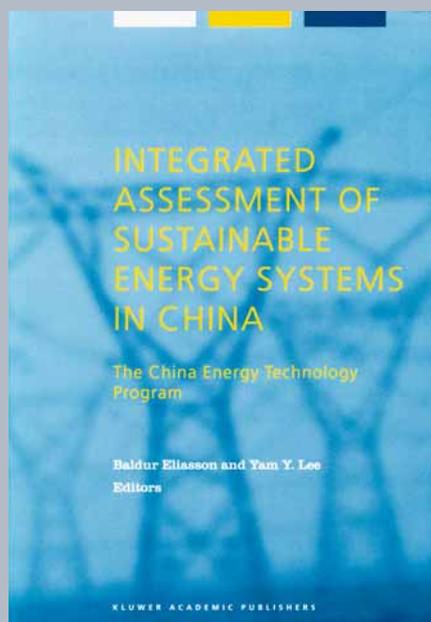
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## The China Energy Technology Program



The increasing global need for electricity – the largest part of which is generated from primary energy sources – is having a significant impact on the environment by the emission of anthropogenic greenhouse gases. Under the auspices of the Alliance for Global Sustainability, alternative strategies giving greater consideration to renewable energy sources have been the focus of a study, the China Energy

Technology Program or CETP. The work was led by ABB in cooperation with universities of world renown and three Chinese research centers. The aim was to identify and analyze the cradle-to-grave impact of a range of power generation options for sustainable growth, focusing on the needs of Shandong, a rapidly developing coastal province located between Beijing and Shanghai.

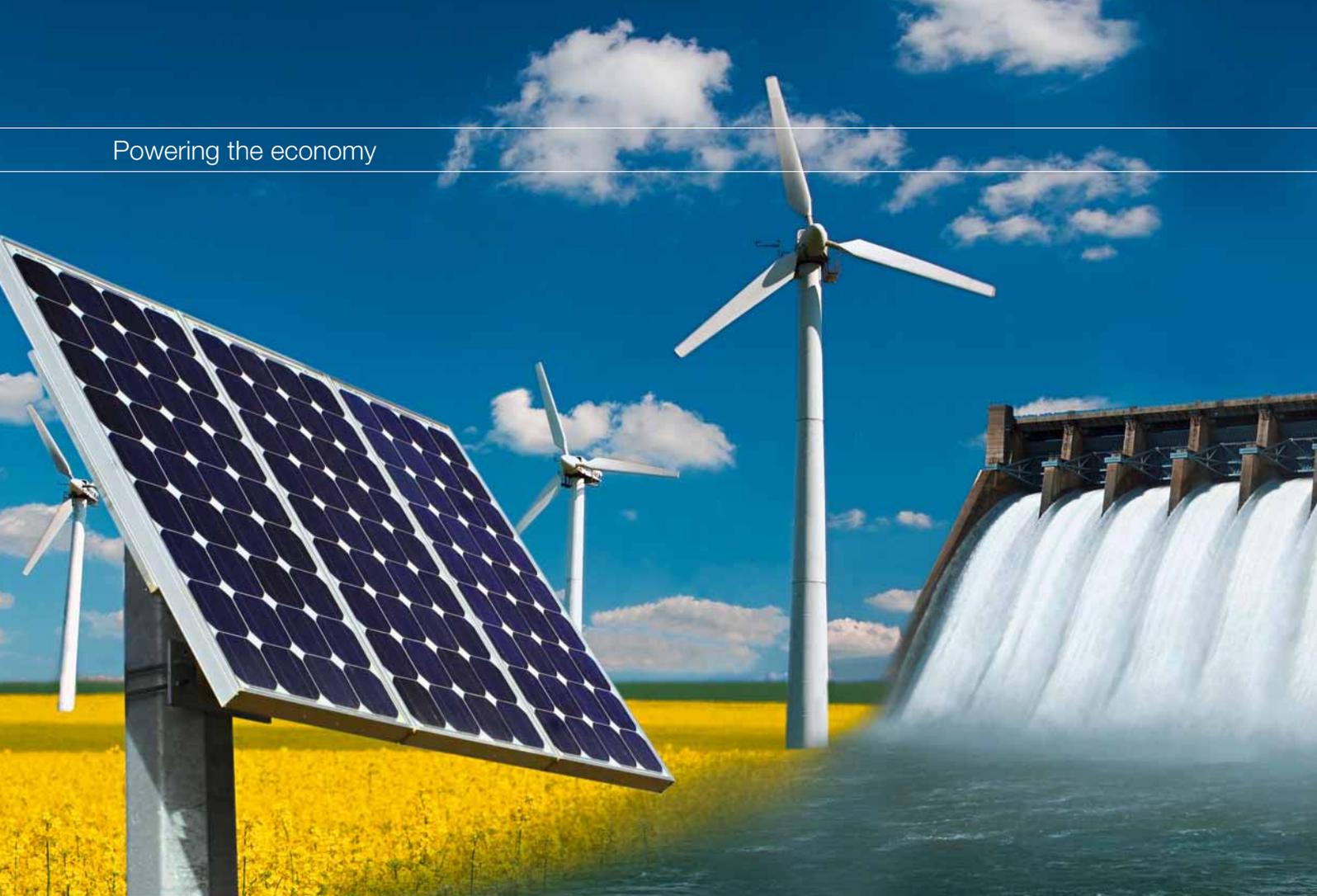
Some 70 scientists, engineers and academics of electricity from three continents contributed to this comprehensive three-year study, as did customers and consumers. The results were published in 2003 under the title “Integrated Assessment of Sustainable Energy Systems in China.”

In this publication, the CETP project group presents an integrated view considering not only the short-term techno-economic parameters but also the long-term environmental aspects of the available options. The encouraging results for Shandong province can be summarized in a few bullets:

- It is economically feasible and socially justifiable to generate more electricity with less air pollution.

- Cost-effective methods and technologies exist that reduce air pollution and stabilize green house gas emissions.

The technologies, the tools and the methodology developed within this program are certainly aimed at being universally applicable to situations similar to Shandong. Decision makers in China or elsewhere will be able to make better and more informed decisions related to the selection of appropriate technologies for electricity generation. As the Secretary General from the Ministry of Science and Technology of the People’s Republic of China, Mr. Dinghuan Shi, expressed: “The policy makers who read this book will most certainly find it invaluable in developing a sustainable system of energy production that will support China’s development goals. I am very glad to have been part of this successful project and look forward to continued international cooperation as the future unfolds.”



# A wind of change for energy production

Sustainable energy for the future

Markku Rissanen, Aiken-Xuan Liu

Demand for energy is ever increasing, especially in fast-growing economies like China. Such heavy demand is frequently at odds with the environment. Pressure to reduce greenhouse gas emissions has created the impetus to use existing energy more efficiently and to explore alternative, more sustainable energy sources. ABB is active in the areas of both energy efficiency and renewable energy, operating under the philosophy that the greenest energy is the energy saved.

Increased worldwide awareness that human activities affect the environment has led to a greater interest in renewable energy, an area that has been a focus of ABB's work for some time. The oldest and best established renewable energy source is hydroelectric power, but more recently other sustainable energy sources have been developed, the most popular being wind, solar and the expanding use of biofuels. Tidal and geothermal energy are also gaining popularity; however, these are less likely to play a significant role in the immediate future.

### Wind power

It is not generally known that ABB is a major supplier of components to many wind-power construction projects, supplying almost everything except rotor blades and towers **1**. ABB is a large supplier of generators in the range of 1 to 5 MW. The wind turbines drive the generators, converting kinetic energy into electrical energy.

ABB's motors, drives, transformers, switchgear, converters, low-voltage equipment and power-plant solutions all contribute to the efficient production and management of high-quality electricity.

## ABB is a major supplier of components required for wind farm construction projects.

Before leaving the tower, a transformer steps up the voltage produced by the generator from 690 V to more conventional voltage levels, eg, 33 kV for transmission. ABB is a world leader in the supply of these transformers. Low-voltage equipment provides relay protection and converters within the towers are used to improve the quality of the electricity generated and reduce stress on the gear box.

**1** ABB – the world leader for products and systems for the wind power industry



Frequently, wind farms are in remote regions, far away from the consumer. This is particularly true for offshore wind parks. The electricity generated in such isolated regions must be transported efficiently over long distances to consumers on land, sometimes many miles from the coast. ABB supplies both AC and DC cables to deliv-

#### Factbox Reactive power compensation

Reactive power describes the loss of power in a system resulting from the production of electric and magnetic fields within it. Reactive loads in a power system drop voltage and draw current, which creates the impression that they are using up power, when they are not. This "imaginary" or "phantom" power is measured in Volt-Amps-reactive (VAR). It is significant because it must be present to ensure a continuous, steady voltage in transmission networks. If elements of the power grid have an inadequate supply of reactive power from nearby sources, they will pull it across transmission lines, destabilizing the grid. Correct management of reactive power is essential to maintain grid stability and avoid potentially widespread major blackouts.

er this electricity. The wind turbines are connected to a platform housing switchgear, medium-voltage switches, additional transformers and control equipment, where the electricity is stepped up to an even higher voltage. It is then transported onshore, either by a three-phase AC cable or, after an additional conversion to DC, via a HVDC Light® transmission system<sup>1</sup>.

Generally, AC is used for shorter transmission distances and smaller wind-turbine installations, while DC is used for longer distances and larger wind parks. HVDC Light provides additional benefits when transmission is required to join remote power generators to their nearest associated grid, perhaps several hundred kilometers away.

To maintain power quality and reduce voltage flicker (AC voltage fluctuation) often associated with renewable power, ABB offers for AC transmission, static VAR compensation (SVC)<sup>2</sup> equipment, which can provide fast-acting reactive power compensation **Factbox**. Furthermore, ABB's Network Manager™ Supervisory Control and Data Acquisition (SCADA) system provides a means by which to survey and manage the ever-changing demands of today's complex power networks. ABB personnel can assist planners with pre-studies and cost calculations for the installation of individual wind towers or whole wind parks, as well as providing other support services.

ABB's strength lies in its ability to offer complete solutions for the technical and electrical challenges that wind power creates, especially to harmonize their connection to the electricity grid. One of the challenges is that wind power creates an uneven electricity supply – no wind, no electricity

#### Footnotes

<sup>1</sup> HVDC – high-voltage direct current

<sup>2</sup> A static VAR compensator unit uses circuit breakers to regulate voltage, absorbing or supplying reactive power to provide system stability.

## Powering the economy

– and that wind turbines are sensitive to disturbances at the often unstable extremities of the grid, which can cause them to shut down.

Wind power is important for the global environment. In countries like China it is essential to encourage the development of sustainable energy sources from the outset to meet increasing demands for energy.

The Jiangsu Longyuang wind farm north of Shanghai was initiated in 2005 and has 67 wind turbines linked to the grid **2**. The location was chosen for its sparse population and for its exposure to persistent coastal winds. From an early stage in this project, ABB provided practical advice, drawing on its long years of experience in the wind farms of Europe. ABB supplied power equipment for the Chinese wind farm, including a compact secondary substation with distribution transformers and a ring main unit, manufactured in China by the ABB Shanghai Transformer Company, Ltd and the ABB Beijing High Voltage Switchgear Company, Ltd. This equipment is used to feed electricity from the farm into the local transmission network, generating around 230,000 MWh of clean electricity each year. By replacing the volume of fossil-fueled power generation, the wind farm avoids almost 200,000 tons of carbon dioxide emissions every year.

Although the portion of the total electricity generated by wind farms worldwide is currently small, rapid growth is underway. China is the world's fastest growing wind-energy market, where the average growth rate has been 56 percent a year for the past

seven years **3**. The installed capacity was 5.9 GW at the end of 2007 and is expected, according to the Chinese Renewable Energy Industries Association (CREIA), to grow to 50 GW by 2015.

### ABB China supplies equipment used to feed electricity from wind farms to their local transmission networks in China.

Although most wind farms are currently on land, the most effective wind parks are offshore, where the wind is stronger and more persistent. The popularity of such offshore wind farms is increasing and ABB's expertise and advanced technology will continue to play an important role in the efficient transmission of electricity from wind parks to the grid.

The largest wind-park project in Europe is the Borkum E.ON scheme off the north coast of Germany. The wind park, comprising 80 turbines located about 130 km from the coast, will generate 400 MW. The power will be fed into the German electricity grid using ABB's HVDC Light technology **4**.

Similar large offshore wind parks are projected in China, close to the densely populated electricity load centers in the east of the country, where supplies of clean power will reduce the number of conventional power stations needed. Of course China is no stranger to ABB's HVDC Light technology. The State Grid Corporation of China (SGCC), together with ABB, has built four HVDC power transmission

systems since 1989, connecting the coastal cities of Shanghai, Guangdong and Changzhou to clean hydropower generated at the Three Gorges hydroelectric power plant some 1,000 km to the west.

Recent technical advances have increased long-distance power transmission. Together, SGCC and ABB, are building the fifth high-voltage DC line – an 800 kV ultra-high-voltage direct current (UHVDC) transmission link to connect the Xiangjiaba hydropower plant in southwest China to Shanghai, more than 2,000 km away. This will create the longest transmission line in the world, connecting a remote hydroelectric power plant to the densely populated regions of eastern China. Such use of sustainable power production will avoid the combustion of 40 to 50 million tons of coal and 100 million tons of CO<sub>2</sub> emissions annually.

### Solar power

In addition to wind and hydroelectric power generation, China is active in solar-energy production. According to the China Association for Standardization, about 90 percent of all the hot water used in the Olympic village is solar heated, and 80 to 90 percent of the streetlights around the Olympic venues are solar powered. Although currently on a small scale, such initiatives are planned across the nation, with projected plans for solar streets in major cities.

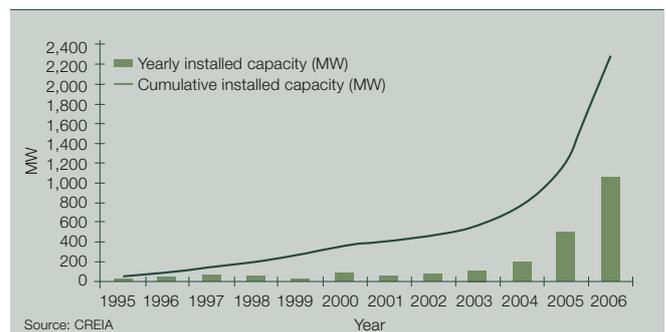
Solar energy consists of three main technologies:

- Solar thermal heating: Solar collectors are used to heat a fluid, which in turn is used for heating purposes.

**2** The Jiangsu Longyuang wind farm on the eastern coast of China



**3** Wind power energy market China



4 Offshore wind turbine connected by ABB submarine cabling



5 Parabolic troughs in fields facing the sun



- Photovoltaics (PV): Solar cells are used that convert solar radiation directly into electricity.
- Solar thermal power generation: Focused solar radiation provides the energy to turn water into steam, which then drives a turbine to generate electricity.

The power generated at solar plants can be delivered to the local grid via ABB power transformers, converters, motors and other substation equipment.

Although solar energy lags behind wind-power and hydropower production, there is huge potential to generate clean solar energy in China. Two-thirds of China's land mass receives more than 2,000 hours of sunlight annually, more than many regions of the same latitude in Europe. This equates to an estimated potential solar-energy reserve equivalent to 1,700 billion tons of coal.

China is already a major player in the solar-energy market. The latest market surveys concluded that Chinese solar cell production surpasses that of both Japan and Germany, and its products dominate the global solar market.

Although most solar-energy installations are less than 100 kW, there are some larger installations in the MW range. In fact, plans to install solar plants in the range of 300 to 500 MW were announced recently in the United States, to be completed around

2011. ABB is well placed to assist with such projects with its broad portfolio of power and automation products and systems.

One large solar plant for which ABB has supplied products is the Andasol plant in southern Spain. Located in the Sierra Nevada in Andalusia, it will be the largest solar plant in Europe and one of the largest in the world, when completed in 2009. It will be the first in Europe to use parabolic troughs to capture solar radiation and generate electricity on a commercial scale, and only the second in the world to do so <sup>5</sup>.

Andasol 1 and 2 will each generate 50 MW of electricity by concentrating sunlight in two solar fields of trough-shaped parabolic mirrors. The technology collects the solar radiation as heat using mirrors that track the sun and concentrate solar radiation onto a collector tube installed at the focal point of the mirrors. Heat-transfer fluid passing through the tube delivers the heat to produce steam, which drives a turbine to generate electricity. The two plants will produce about 350 GWh of electricity per year, enough to supply 100,000 households and avoid 345,000 tons of greenhouse gas emissions a year. These plants are controlled by ABB's Extended Automation System 800xA and ABB Power Generation Portal software. The power generated at the plants will be delivered to the local grid via ABB power transformers, converters, motors and other substation equipment.

Similar solar energy plants in the 100 to 300 MW range are planned worldwide.

### Biofuels

Biofuels are an additional source of sustainable energy and one of special interest to the automotive industry <sup>6</sup>. The choice of biofuel sources is large, but each source provides different levels of energy efficiency and sustainability.

According to the National Guidance Catalogue of Renewable Energy Industry Development, China is focusing on the development of bioethanol and biodiesel technology, Bagasse combined heat and power (CHP) technology, crop-straw power generation, biomass solidified fuels, landfill gas utilization, medium to large scale biogas projects and small household biogas digesters.

China has the largest bioethanol plant in the world producing 350 million liters of ethanol from corn a year.

With a production of about 14 million m<sup>3</sup> per year, Brazil is currently the largest producer of ethanol from biofuels derived from sugar cane. For a long time, the United States had been the second-largest producer, but is now producing about as much as Brazil using corn. In China, the biofuel industry is expanding, and in 2004 Jilin Fuel Alcohol Company Limited built the largest bioethanol plant in the world, producing 350 millions liters of ethanol from corn a year. In Europe the most active countries in biofuel production are Spain, France and Germany.

## Powering the economy

6 Cars are increasing in number especially in countries like China.



ABB's role in the biofuel industry has been to deliver control systems and instrumentation to plants in Germany, Thailand, Canada and the United States 7. Most of the plants use ABB's Automation System 800xA with AC800M process stations and Profibus for communication.

Biogas is an expanding market in biofuels. In China, the targets for biogas electric power generation with "feed-in-grid" capability are projected to be 0.8GW by 2010 and 3 GW by 2020. In addition, landfill gas is projected to supply an additional 0.2GW by 2010 and 1.0GW by 2020. For China, biofuels are expected to deliver about 18 percent of the country's sustainable

energy by 2010 and are expected to continue to do so until 2020. ABB's technology could provide the process control systems and integrated safety oriented instrumentation to automate the biogas-powered electric generators, as well as the equipment required to connect the electricity generated to the grid.

### China's future renewables market

In 2005, 7.5 percent of energy consumed in China was derived from renewable sources, equivalent to 166 million tons of coal, avoiding 400 million tons of CO<sub>2</sub> emissions. The Chinese government predicts that 10 percent of all energy consumed in China by 2010 will be from

7 ABB's solutions for bioethanol production



renewable sources, reaching 16 percent by 2020 8. This means that by 2010, the consumption of renewable energy will reach the equivalent of 300 million tons of coal, avoiding 600 million tons of CO<sub>2</sub> emissions.

The Chinese government predicts that 10 percent of all energy consumed in China by 2010 will be from renewable sources.

New technologies and innovations will help countries around the world reduce their reliance on fossil fuels. ABB's market leading and award-winning portfolio of energy supply solutions drives the company to a strong active position to help deliver a greener future.

8 Renewable energy in China

Items	2000	2005	2010 (Plan)
Power generation			
1. Hydropower (MW)	79,350	110,000	190,000
2. Grid connected wind farm (MW)	340	1,260	10,000
3. Off-grid wind farm (MW)	30	50	75
4. PV generation (MW)	19	70	300
5. Biomass generation (MW)	170	2,000	5,500
Biomass (billion m <sup>3</sup> )	3.5	8	19
Biomass in rural (M home)	8.5	18	40
Heat			
1. Solar water heater (Mm <sup>2</sup> )	26	80	150
2. Geothermal (k ton standard coal)	1,200	2,000	4,000
Fuel			
1. Alcohol (k ton)		1,020	3,000
2. Biodiesel oil (k ton)		50	200
Total (M ton standard coal)	12	16.6	30

Data source: The Five-Year Plan for renewable energy issued by National Development and Reform Commission

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# Saving energy the efficient way

ABB's products are energy efficient helping to reduce energy wastes around the world.

Bin Su, Markku Rissanen



Electricity is increasingly important in today's modern society. Most primary energy sources are converted into electricity to meet relentless demands. The inefficient use of energy means that three-fifths of our energy capacity is lost. Greater energy efficiency not only helps to conserve limited fossil-fuel resources but also helps to reduce carbon emissions.

The efficient use of energy is regarded as a solution to the energy crisis. From producer to consumer, there is great potential to save energy. ABB's profolio of products and services can contribute to greater energy efficiency from power generation and transmission to distribution and consumption.



## Powering the economy

Energy losses due to inefficiency are huge. Needless wasted energy could be prevented by increasing the efficiency of all aspects of power production right through to consumption. By installing energy efficient equipment, countries with rapidly expanding economies, like China, could reduce their demands on world resources and reduce harmful emissions **1**. In China, coal is by far the largest contributor to electric power generation, accounting for 65 percent of China's energy consumption. This amounts to 28 percent of the world's total coal consumption. Clearly, by encouraging the use of the most efficient methods of power generation in China and around the rest of the world, the impact of thermal power generation plants on fossil-fuel reserves and the environment will be significant.

### ABB's combustion management software optimizes the combustion process in thermal power plants to improve efficiency.

#### Power generation

By optimizing the energy conversion process, huge savings in energy losses can be made. Since such large quantities of fuel are used in this process,

even minor improvements in efficiency can have a dramatic overall effect.

One of the most important processes in a thermal power plant is combustion. Water is heated to produce steam, which drives steam turbines linked to electric generators. The control of this process is very complicated, yet improvements made here are critical to the efficiency of the power plant. ABB's combustion management software package improves boiler control; allows the flame quality to be monitored; and measures and controls the flow of fuel and air to increase combustion efficiency, reducing nitrogen and carbon monoxide production.

The heart of the combustion management system is the Optimax® combustion optimizer. For closed-loop combustion optimization of coal-fired boilers, the ABB Neural Net modeler replicates the multivariable, nonlinear relationships of the combustion process. This approach is especially suited to the complex combustion process, which cannot easily be described in mathematical terms. The model predictive control (MPC) in combustion management is a generated multivariable, dynamic controller and optimizer that uses dynamic feedback to update the models. A unique characteristic of the software is its ability to learn and predict trends so that re-

sponse times to changing conditions can be reduced, resulting in greater efficiency.

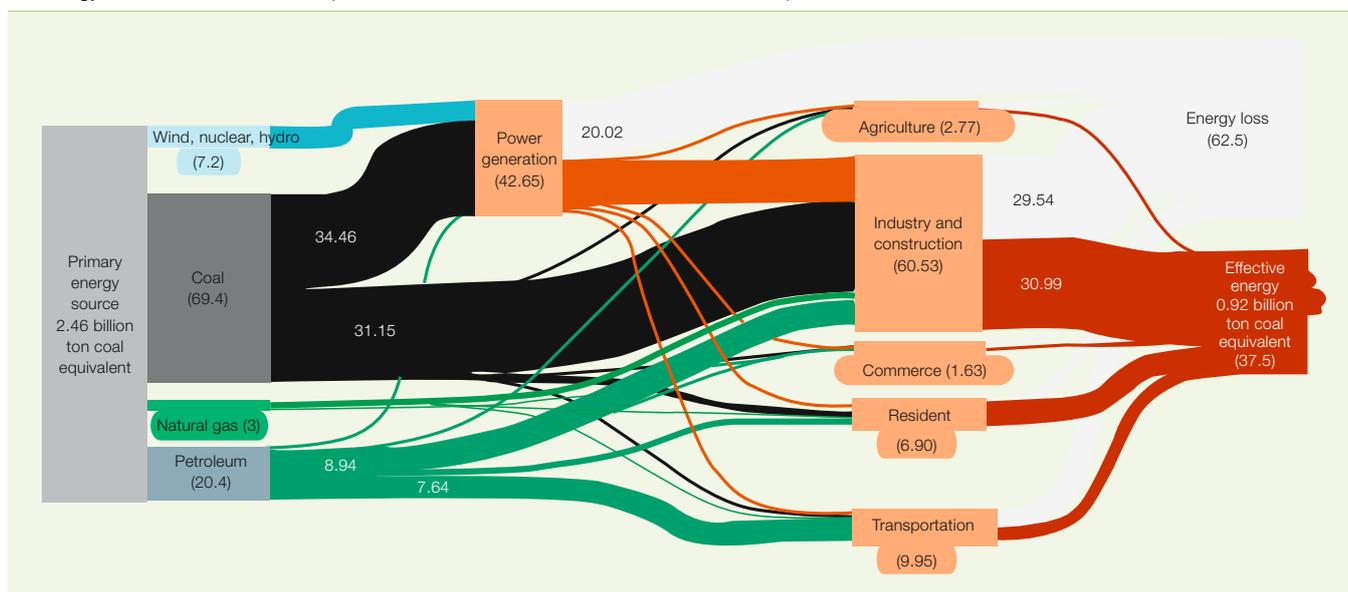
Taking an optimized 600MW unit in the European Union as an example, the benefits can reach:

- Equivalent to \$80 million CO<sub>2</sub> certificates over a lifetime<sup>1)</sup>
- Increased plant output of more than 15 MW
- Plant efficiency increases of 1.5 percent

ABB built a district heating system in Harbin, China that uses the heat normally wasted in a power station's cooling tower to heat homes in the district.

Optimizing the combustion process is one step towards increasing energy efficiency, but often thermal power plants simply vent the heat generated for steam production through cooling towers into the environment once it has passed through the turbines. This heat is a huge source of wasted energy. In 2007, ABB built a large district heating system in Harbin, China, creating a new central combined heat and power (CHP) plant that uses the heat normally wasted in a cooling

**1** Energy flow chart in China 2006 (Data source: National Bureau of Statistics of China)



## Powering the economy

tower to heat homes in the district. Such cogeneration plants and district heating networks help reduce energy consumption and overall emissions, since they eliminate the need for individual boilers in the home and reduce the wasted energy from conventional power plants.

### Power transmission and distribution

Today, electric power is frequently transported long distances from its source of generation to the consumer. High-voltage direct current (HVDC) is the most energy-efficient technology available for long-distance bulk power transmission, losing less electricity than conventional AC transmission systems. The existing three  $\pm 500$  kV HVDC lines used to transport electricity from the Three Gorges hydroelectric power generation plants to consumers in eastern China have already saved sufficient energy to avoid the construction of a further 300 MW power station that would be required

if the transfer capability was through AC transmission. A conventional 800 kV AC circuit loses about 7 percent of its electricity over 1,500 km, while only 6 percent is lost over the same distance with a  $\pm 500$  kV HVDC circuit. An even greater saving with losses of only 5 percent can be made with a  $\pm 800$  kV ultra-high-voltage direct current (UHVDC) circuit carrying 6 GW.

To develop 800 kV UHVDC technology all equipment had to be redesigned and tested to ensure reliability at higher voltages.

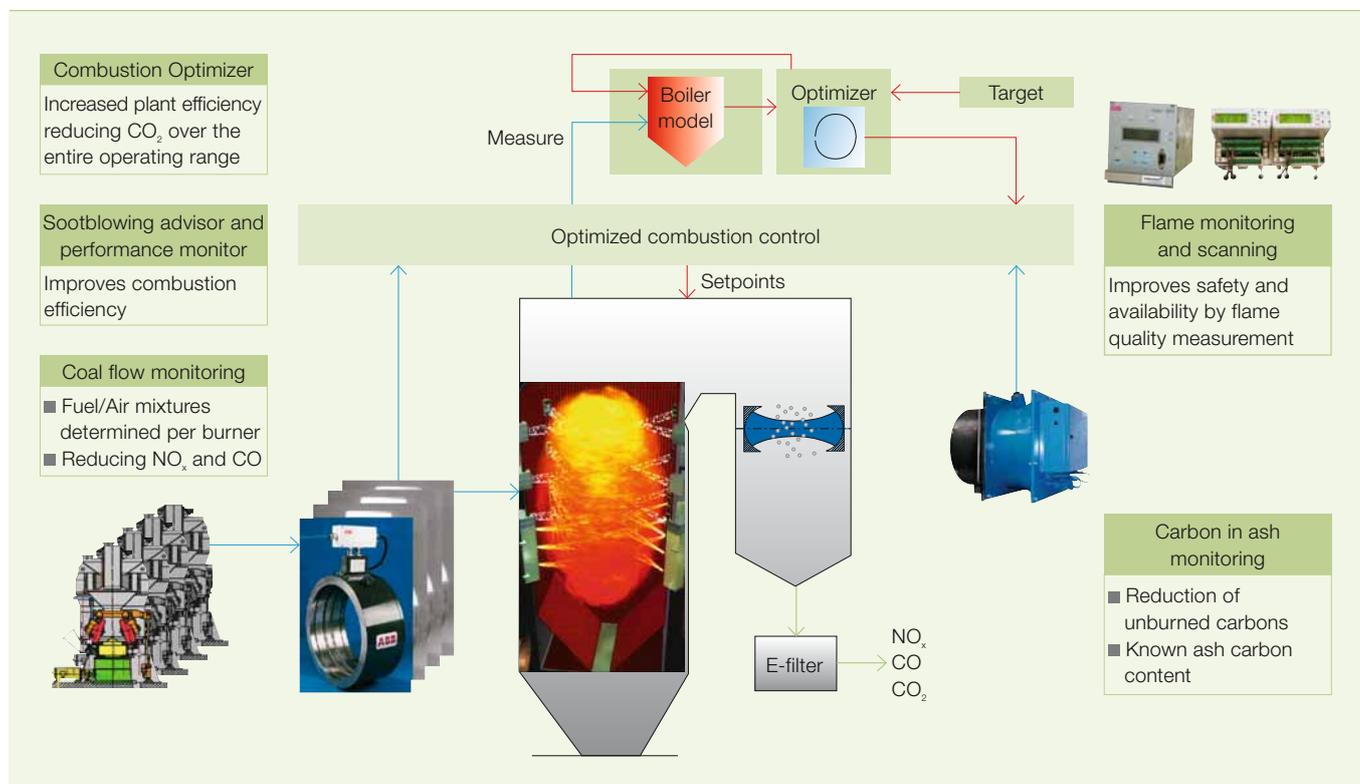
The key to the development of  $\pm 800$  kV UHVDC technology is the insulation and the design of the main circuit for high reliability.

To produce a  $\pm 800$  kV UHVDC transmission system, ABB has designed, manufactured and tested transformers, transformer bushings, wall bushings in the valve hall, thyristor valves, arresters, voltage dividers, DC filter capacitors and support isolators specifically able to withstand such high voltages.

For higher reliability, the main circuit of the converter station was specially designed . Two 400 kV 12 pulse converters are connected in series. When one converter is tripped, another converter can continue to transmit half-rated power. The forced availability of  $\pm 800$  kV UHVDC can reach 99.9 percent.

The world's first  $\pm 800$  kV UHVDC transmission system is under construction in China and will be operational in 2010, transporting electricity from the huge Xiangjiaba hydroelectric power plant in southwest China 2,000 km to Shanghai in the east.

## 2 Combustion optimization



### Footnotes

<sup>1</sup> CO<sub>2</sub> certificates allow emissions trading supported by the Kyoto Protocol. A ton of CO<sub>2</sub> is given a trading value (eg, 20 euros) so that 230,000 tons of CO<sub>2</sub> emissions are worth about 4.6 million euros or \$5.5 million.

<sup>2</sup> Reactive power describes the loss of power in a system resulting from the production of electric and magnetic fields within it. Reactive loads in a power system drop voltage and draw current, which creates the impression that they are using up power, when they are not. This "imaginary" or "phantom" power is measured in Volt-Amps-reactive (VAR).

## Powering the economy

### HVDC Light®

One of the main obstacles to large-scale offshore wind-park power utilization is reliably and efficiently connecting the electricity generated to the power grid, especially if the grid is weak. HVDC Light® is a power-transmission system that enables such reliable long-distance electricity delivery from offshore wind farms to distant population centers. This helps provide sustainable energy solutions to the ever-increasing demand for electricity without contributing to further CO<sub>2</sub> emissions. The capability of HVDC Light comes from voltage source converter (VSC) and cross-linked polyethylene (XLPE) DC cables.

HVDC Light is a power-transmission system that enables reliable long-distance electricity delivery from offshore wind farms to distant population centers.

The VSC used in HVDC Light allows independent control of both active and reactive power<sup>3)</sup>, providing the best combination of each to stabilize the grid **4**. Such regulation is critical for voltage and frequency control in the power grid and is essential to stabilize power fluctuations inherent to wind farms.

XLPE DC cables avoid the reactive charging power of AC cables and allow efficient power transmission over long distances **5**. Two major obstacles had to be overcome in order to develop XLPE DC cables:

1. The space charges in the insulation that can lead to local uncontrolled high electric fields that cause dielectric breakdowns had to be prevented.
2. Uneven stress distribution in the outer part of the insulation caused by temperature-dependent resistance had to be avoided.

The German utility E.ON has awarded a contract to ABB to supply the power equipment that will integrate the world's largest offshore wind farm with the existing German power grid. The wind farm consists of 80 wind turbine generators of 5 MW located about 130 km from the coast in the North Sea. The generators will feed power into a 36 kV AC cable system, which will be transformed to 154 kV for the HVDC Light offshore station. The receiving station will be located on land, 75 km from the coast at Diele, where the power will be introduced into the German 380 kV grid

**Factbox**

### Distribution transformers

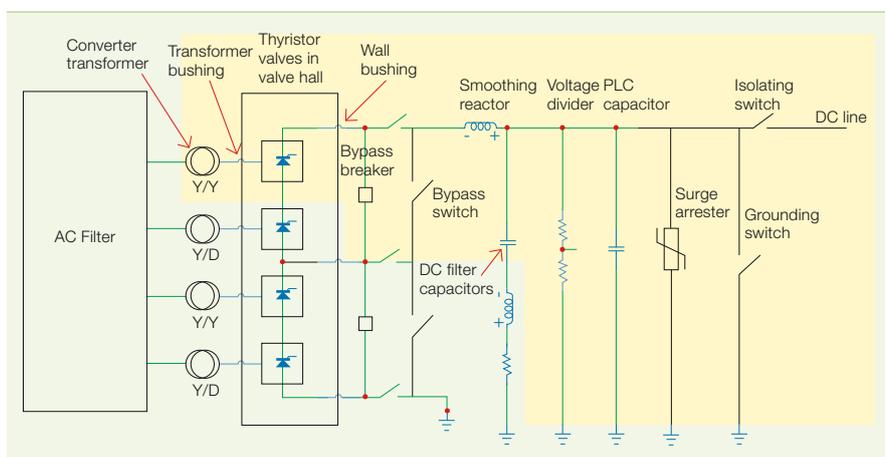
Distribution transformers are responsible, after transmission lines, for the next-largest electricity losses in networks. Now, modern technology exists to reduce these losses by up to

80 percent. The worldwide electricity savings potential of switching to high-efficiency transformers is estimated to be at least 200 TWh. The losses made by distribution transformers consist of no-load losses<sup>3)</sup> and on-load losses<sup>4)</sup>. No-load losses can be reduced by selecting high-performance steel for the core. Over the years, better steel for transformer cores have been developed. Various processing and coating techniques and reduced silicon content have led to the creation of high-permeability grain-oriented steels (HiB). They remain the current standard material for manufacturing distribution transformers in Europe. During the 1980s, techniques were introduced to refine the domain of the iron crystals by laser etching, and more recently, the development of amorphous iron introduced a significant new evolution for reducing iron losses.

ABB's award-winning S11 rolling-iron core distribution transformer produced in China is helping clients decrease power losses during transmission and distribution.

In addition to the choice of the steel, the way in which distribution transformer cores are designed, cut, fabricated and assembled plays an impor-

**3** AC to DC converter



**Factbox** Specifications for German utility E.ON offshore wind farm

Main data	
Commissioning year	2009
Power rating	400 MW
AC voltage	170 kV (offshore), 380 kV (Diele)
DC voltage	±150 kV
Length of DC underground cable	2 x 75 km
Length of DC submarine cable	2 x 128 km

### Footnotes

<sup>3)</sup> No-load losses: The power loss of a device that is operated at rated voltage and frequency, but is not supplying power to a load.

<sup>4)</sup> On-load losses: The sum of the copper loss of a transformer, due to resistance in the windings, plus the eddy current loss in the winding, together with stray loss.

tant role in energy efficiency. Increasing the size of the core reduces the density of the magnetic field, and in this way improves energy efficiency. ABB's award-winning S11 rolling-iron-core distribution transformer produced in China is helping clients decrease power losses during transmission and distribution.

Amorphous iron deserves a special mention. Distribution transformers built with amorphous iron cores can have more than 70 percent lower no-load losses compared with the best conventional designs, and achieving up to 99.7 percent efficiency for 1,000 kvar units. These transformers have cores wound with amorphous ribbon made from a ferric metal alloy produced by very rapid quenching to avoid crystallization. Currently, amorphous technology has been proven for transformer sizes up to 10 MVA, and its application range is expanding.

**Power consumption**

Huge demand for steel – especially in China – has encouraged steel producers to increase melt capacity and improve power supply. Unfortunately the electric arc furnaces of steel plants

cause fluctuations in voltage when operating, commonly causing flicker and other power-quality problems, especially in weak power grids. These flickers not only affect other electricity consumers, but also reduce the productivity and efficiency of the electric arc furnace itself. Static VAR compensation (SVC)<sup>5)</sup> equipment provides a powerful solution to flicker and improves the power supply to the furnace by providing fast-acting reactive power compensation. ABB is the number-one supplier of SVC worldwide, with more than 400 installations either in service or under construction.

**Power quality and energy efficiency**

ABB's SVC Light<sup>®</sup> technology has been designed with special attention to the severe voltage variations created by electrical arc furnaces. With this new technology, response time is less than one millisecond. SVC Light, like HVDC Light, employs a voltage source converter (VSC) composed of high-voltage switching devices known as insulated-gate bipolar transistors (IGBTs). These devices can switch at very high frequency and allow connections in series. Pulse-width modulation (PWM) is utilized in the VSC

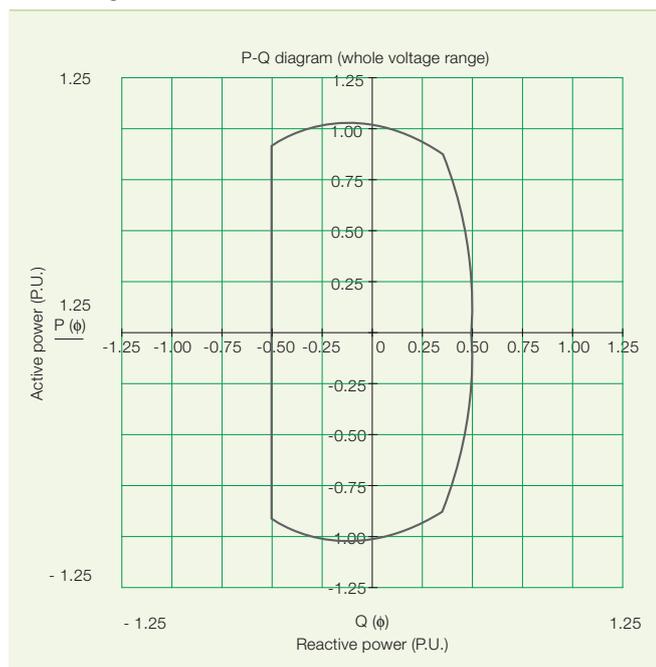
with a switching frequency in the kilohertz range. This high frequency provides a very smooth voltage output from the VSC. The fast response of SVC Light means it can be used as an active filter. An ABB SVC Light device rated at 10.5 kV, 0 to 44 Mvar has been in operation since 1999 at the Uddeholm Tooling AB steel plant in Hagfors, Sweden **6**.

Measurements have been made of the active power consumption at the Uddeholm plant with and without SVC Light. Through dynamic compensation, the stabilized voltage increases

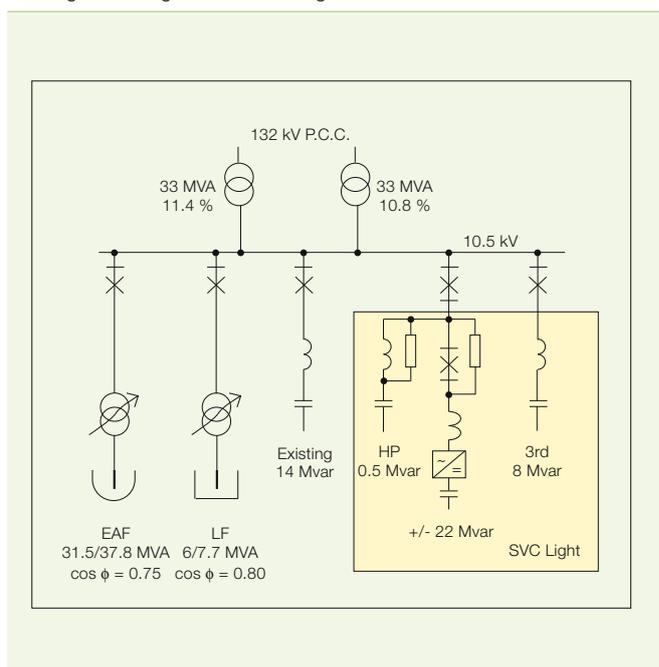
**5** XLPE DC cables.



**4** P-Q diagram



**6** Single line diagram with SVC Light



**Footnotes**

<sup>5)</sup> SVC is a device that provides fast-acting reactive power to compensate for fluctuations in the voltage and current of an electric grid, thereby allowing more power to flow through the network, while maintaining safety margins and increasing network stability.

## Powering the economy

the available furnace power. With SVC Light in operation, the active power increase gives a furnace a production increase from 27.5 to 31.4 metric tons per hour. The active power increase allows a faster melt in the electric arc furnace, thereby saving energy consumption. This saving accrues over time, cutting around 25 kWh of electricity per metric ton of steel melted, thus providing about 4 percent savings to the plant operator.

### Without ABB's SVC Light the Zhangjiagang Pohang Stainless Steel plant near Shanghai could not run at full capacity.

In China, SVC Light has been installed so that the Zhangjiagang Pohang Stainless Steel (ZPSS) producer near Shanghai can run at full capacity, avoiding voltage fluctuations and flicker. Without SVC Light, ZPSS would have to have significantly reduced production capacity in order to stay within the legal parameters

that marshal the flicker effects produced by industry.

#### Intelligent building

Needless energy waste in China's buildings can be estimated in trillions of dollars. By reducing the energy wasted by consumers, less electric power generation would be required in the first place.

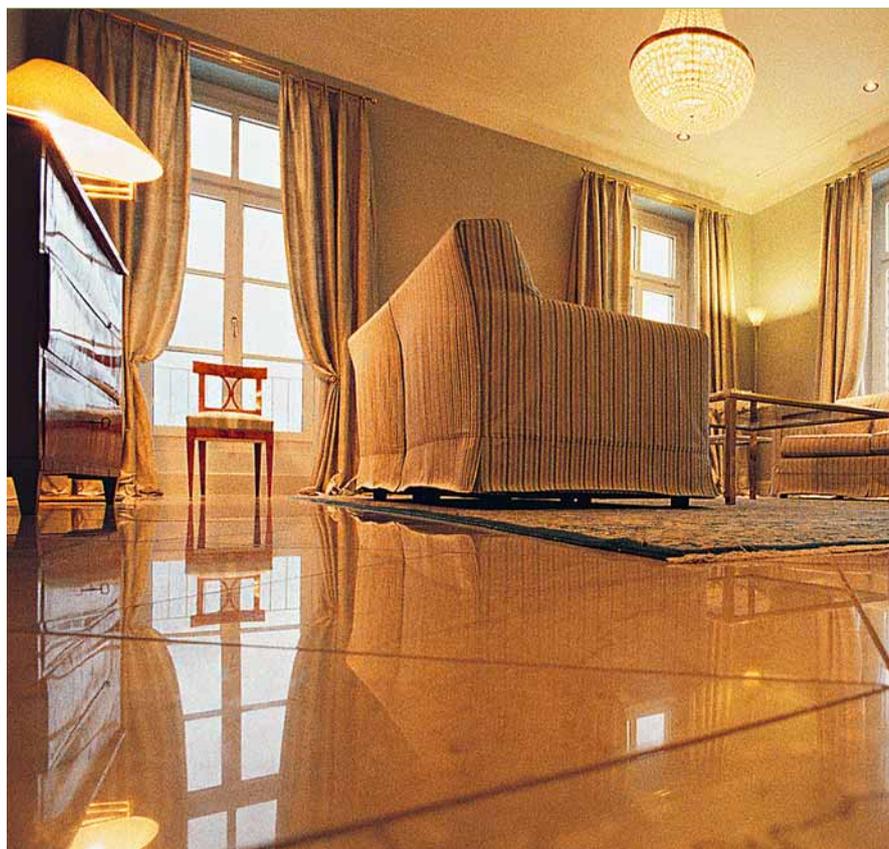
ABB i-bus® EIB (European Installation Bus) is an intelligent building installation system that was introduced in China at the turn of the century. ABB i-bus EIB provides increased security, efficiency, convenience and flexibility, whether in office buildings, industrial plants or residential properties. The system takes care of lighting, sunshade control, heating and cooling and can be tailored to the requirements of the user. Its flexibility is one of its major assets and can be adapted for use in a range of building types, from residential houses to commercial buildings such as exhibition centers, hotels, museums, schools, garages and meeting centers.

Since the introduction of ABB i-bus EIB in China, the ABB i-bus EIB system has been installed at the Xiamen Exhibition and Meeting Center, the Great Hall of Hangzhou, the Exhibition and Meeting Center of Changsha, the Exhibition and Meeting Center of Hefei, the New International Exhibition Center in Shanghai, the Modern Museum of Dalian, the National Library and Meeting Rooms of the Central Government Office Building. Generally, the energy saved by installing such a system covers the cost of installation within half a year of operation. The impact of installing such systems on a country's energy requirements is significant, particularly for a country the size of China.

#### Green shipping

Diesel engines are the main source of propulsion in most of the world's ships. These engines have an ideal operating efficiency range in which fuel consumption and exhaust emissions are optimal, but as soon as the ship slows, this optimal operating speed is lost. The solution is to keep engines running at their most favorable speeds at all times.

7 The ABB i-bus EIB controlling technical building systems.



In the Azipod system, the electric motor is installed inside the pod and no gearbox is required, providing greater efficiency.

With traditional mechanical transmission, running the engines at their optimal speed is not possible, since engine speed is rigidly coupled to the propeller speed. Using electric transmission (generators and motors connected by cables), this is no longer the case. When diesel engines are operating at constant and optimum service speed, fuel consumption is lower than running the same engines at variable speed. In addition, in a geared propulsion system, which involves the slowing down and changing from two-engine mode to single-engine mode, the propeller speed and pitch has to be controlled to avoid overloading the diesel engines.

8 ABB's Azipod system for ship propulsion



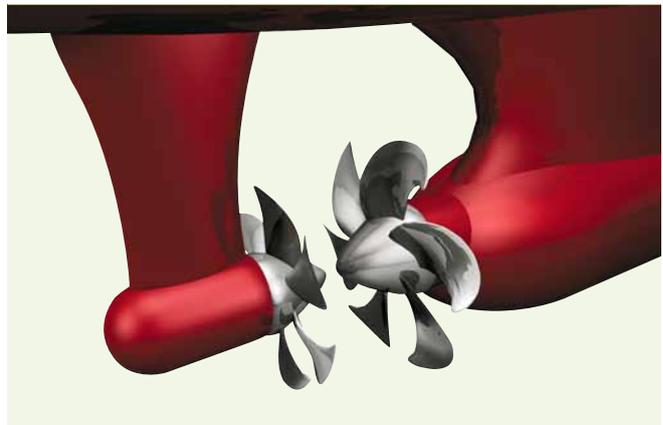
In the Azipod® system, the electric motor is installed inside the pod. The propeller is connected directly to the motor shaft. No gearbox is required, providing greater efficiency <sup>8</sup>. Electric power for the Azipod motor is conducted through slip rings that allow the Azipod unit to turn through 360 degrees. Because fixed-pitch propellers are used in Azipod systems, power for the Azipod unit is always fed through a variable-frequency drive that allows speed control of the propulsion motor.

A further contribution to fuel efficiency is provided by counter-rotating propellers (CRP). These improve the hydrodynamic properties of the propulsion system, reducing fuel consumption. The CRP concept features a novel combination of conventional propulsion and Azipod propulsion. The propulsion systems are arranged

coaxially, but without any physical connection <sup>9</sup>. The pulling propeller of the Azipod unit will rotate in the opposite direction in relation to the main propeller driven through the shaft directly from the diesel engine. There is no need for a conventional rudder because the pulling Azipod unit rotates to maneuver the ship. Both propellers are fed by independent power supplies for greater redundancy. This arrangement allows the recovery of the main propeller's forward rotational velocity.

A study made by Samsung and ABB shows that the efficiency gain from this new propulsion system depends on factors such as ship type, ship speed, power level, loading and so on. In general, an efficiency improvement of 5 to 8 percent is achieved with a CRP system. Because 2 to 3 percent of fossil fuels in the world

9 Counter-rotating propellers (CRP)



are consumed by shipping, the improvement in efficiency has a far-reaching effect on fuel consumption and emissions. In China, ABB's Compact Azipod propulsion system is already saving fuel consumption in ferries and a marine surveillance ship. This technology is expected to be adopted in the near future for use in ultra-large container ships, high-speed ferries and ocean work boats in China.

Counter-rotating propellers one from the ships conventional propulsion system the other from ABB's Azipod can improve efficiency by 5 to 8 percent.

#### Energy efficiency

Increasing energy efficiency is an effective way in which to reduce fuel consumption and carbon emissions. The installation of the most energy-efficient equipment, especially in countries with rapidly growing economies, will have far-reaching effects on the conservation of fossil fuels and contribute to the reduction of carbon emissions.

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# Congestion relief

FACTS – the key to congestion relief

Rolf Grünbaum, Peter Lundberg, Göran Strömberg, Bertil Berggren



From the light that goes on when we flick a switch, to industry's ability to supply us with all the goods and services that we expect, the reliability and continuity of the power supply is something most people have come to take for granted. Not so ABB – the company has a collection of products and technologies, designed to maintain and improve the integrity and continuity of the power supply.

The requirements that are placed on today's grid are changing. Traditional power flows from power stations to the nearest big city are giving way to more complex patterns. Growing consumption and power trading mean that power must increasingly be transported over large distances. Growth in the use of renewable sources is placing a strain on the system because generation is often located in

remote regions where the power grid is traditionally weak. The wholesale construction of new transmission corridors is not always the best option due to a combination of environmental, land-use, permit-granting and cost considerations. The alternative is to make more intensive use of existing infrastructure without compromising reliability. ABB has the technology that makes it possible!

The concept of transmission congestion implies, by definition, that there are limitations to how much power can be transferred across a transmission interface, and further that there is an incentive to actually desire to transfer more power. This incentive is often based on differences in power production costs on either side of the interface – a factor that has become more transparent through recent deregulation measures. In other words, there are consumers on at least one side of the interface who could benefit from being able to purchase power produced on the other side. But before such trading can become viable, the infrastructure must be able to support it.

The traditional approach to remedying congestion lies in reinforcing the system with additional transmission capacity (eg adding overhead lines). Although still feasible, this approach is becoming more and more complex and it is often challenged by the public. It is becoming increasingly difficult and time-consuming to obtain the permits to building new transmission corridors, or even expand existing ones.

An alternative that can postpone or altogether avoid the need for such investments lies in improving the utilization of existing infrastructure by permitting more flexibility and controllability. This can be done through the installation of controllable devices in the transmission system, such as FACTS (Flexible AC Transmission System) devices, possibly supplemented with advanced information gathering systems. Although, in general terms, the concept is commonly accepted, the application of these measures involves a number of challenges requiring attention.

### FACTS solutions for congestion relief

Typically, different solutions can be envisaged – the solution selected depends on the nature of the physical constraint. However, the operational environment in which these solutions are applied is common to all, and the associated control strategies can to some extent be generalized.

In a general setting, the philosophy behind corrective control as applied

to FACTS devices for mitigation is similar to that shown in **1**.

The traditional approach to remedying congestion lies in reinforcing the system with additional transmission capacity (eg adding overhead lines). Although still feasible, this approach is becoming more and more complex and it is often challenged by the public.

#### Dissection of a fault handling scenario

During more than 99 percent of operating time, the focus of the control system is on loss minimization and on loop flow control relative to neighboring networks. Following a disturbance, the control objective instantly changes to handling the physical limitations of the network. Following the clearance of a network fault, transient phenomena must be attended to. These phenomena, which include first swing stability; power oscillation damping (POD); voltage stability/recovery and frequency control, require an adequate speed of control if mitigation is to be successful.

After 10 to 20 seconds, when the transient period is over and the post-disturbance period starts, slower phenomena may require attention. The

control objective switches to address these phenomena, which can include thermal limitations, voltage support (to avoid slow voltage collapse) and frequency support.

After 20–30 minutes the operator should have assessed the situation and taken proper actions to secure a system state that again allows equipment failures without risking such drastic consequences as blackouts.

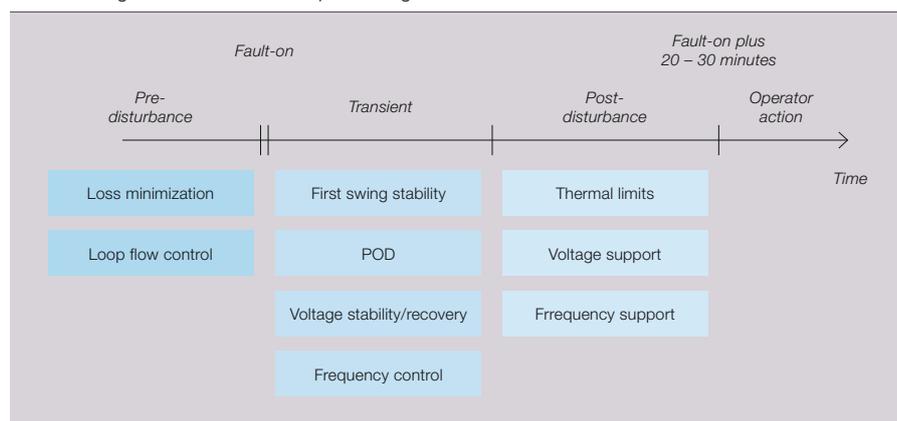
Corrective control applied to FACTS devices is thus a general control strategy that provides means for efficient operation in the pre-disturbance period while still maintaining security in a robust way. Or phrased differently, it is a way to provide the operator with as much time as possible in the event of severe disturbances.

The FACTS devices available provide different means of fulfilling the control objectives indicated in **1**. FACTS solutions are usually subdivided into shunt compensation and series compensation.

#### SVC and STATCOM

Static VAR Compensators (SVC) and Static Compensators (STATCOM) are shunt-connected at critical locations in the transmission grid. Both device types use power electronics to dynamically control the generation or consumption of reactive power. This reactive power is exchanged with the grid to control the system voltage. In addition to providing dynamic voltage support in both the short and long time perspective, these devices are

**1** Corrective control objectives – setting the right priorities is the key to mastering the disturbance and preventing blackouts.



## Powering the economy

capable of providing power oscillation damping in the transient period [1].

The main features of the SVC, the classical FACTS device, are described in [2].

STATCOM [2] is built on the power electronic concept of voltage source conversion. The ABB version, SVC Light®, uses IGBTs. This type of converter enables high performance features such as:

- Robust voltage support under severe disturbances
- Balancing of asymmetrical and rapidly fluctuating loads
- Power oscillation damping
- Active filtering of harmonic currents

SVC Light is described in [3] and [4] for a number of applications where high performance is needed.

During more than 99 percent of operating time, the focus of the control system is on loss minimization and on loop flow control relative to neighboring networks.

### STATCOM with Energy Storage

An optional enhancement of SVC Light is an energy storage feature consisting of series-connected batteries [3] [5]. The size of the energy storage depends on the optimization of performance versus cost. The discharge time, ie operating time at full active power, is in the order of 15 to 30 minutes in the base case. Energy storage enables the STATCOM to also deliver and consume active power during a period of time.

The voltage source converter (VSC) uses series-connected IGBTs to deliver high performance and high power. The battery charge must be controlled throughout the complete load cycle. A typical application example is in conjunction with a renewable energy source such as a wind farm that has a strongly fluctuating production. The load balancing function with energy storage delivers active power at a

- 2 STATCOM (static compensator) equipment performs dynamic voltage control by producing or consuming reactive power.



scheduled power level and reactive consumption/production within operational limits, according to the set-point from the dispatch center.

Thus, the combination of a renewable energy source and a STATCOM with energy storage can permit this otherwise intermittent source of energy to be used in the same way as a conventional production source<sup>1)</sup>.

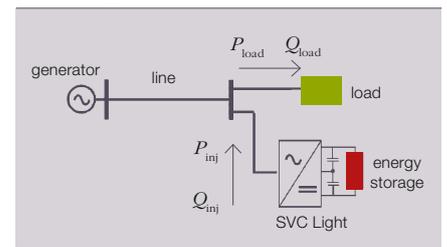
Other benefits for the power system are the use of such devices in emergency operations for black starts or reconstruction of the network using the available frequency and voltage controls. With a STATCOM capable of modulating both active and reactive power output, power oscillation damping can be greatly improved. This permits higher power transfer levels and so relieves congestion.

In principle, energy storage solutions are able to change the time at which a given power-flow across a congested interface occurs (if the storage solution is installed on the receiving side of the transmission corridor). Energy is stored in absence of congestion, and discharged when congestion returns. On the scale of a power grid,

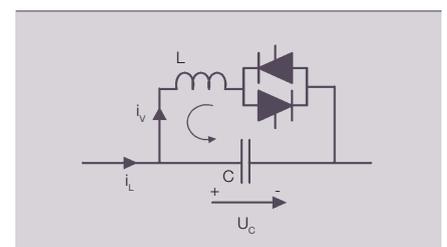
### Footnote

<sup>1)</sup> Intermittent sources of energy such as wind turbines normally require a spinning reserve of conventional power plants to back them up should availability drop. A measure such as this which permits energy to be buffered allows such reserves to be dispensed with or deployed otherwise.

- 3 Dynamic energy storage with SVC Light



- 4 Schematic configuration of TCSC (thyristor controlled series compensation) – TCSC permits variable series compensation



- 5 TCSC equipment used for power oscillation damping



the energy storage capability that would be required would be too large to be feasible. However, for individual consumers, it may be an economically viable solution – in particular when there are power quality problems to be addressed.

A further application of STATCOM with energy storage would be as a frequency-controlled active disturbance reserve, in particular if it is installed on the receiving side of a frequently congested interface. Such an installation could additionally reduce the gap between transmission capacity and trading demands.

#### Thyristor Controlled Series Compensation (TCSC)

Other FACTS devices also have the ability to affect active power flows, even if they do not have energy storage capabilities. In particular, series devices can be used for this purpose.

TCSC [4] [5] is often used at bottlenecks in which the power transfer limit is determined by poor damping of power oscillations. The technology has in particular been proven effective for situations where weaknesses in the transmission grid tend to split the system into two separate large groups of generators. The solution typically involves fixed series compensation combined with a smaller thyristor-controlled section. The latter is controlled to actively dampen the power oscillations. This more precise matching of damping to line conditions permits a larger power transfer [6].

The essential principle of TCSC is that the forward-biased thyristor is fired just before the zero voltage crossing at the capacitor. This injects additional current into the capacitor and increases the apparent reactance, typically up to a factor of three times the original reactance. This variation, which is referred to as boosting, helps mitigate the power oscillations. Contrary to the fixed series capacitor, the TCSC appears inductive in the frequency range below its fundamental frequency, thus effectively eliminating concerns for SSR (sub-synchronous resonance) for the TCSC part in relation to nearby turbine generators.

Lately, the ability to additionally perform active power flow control in the steady state has received increasing interest, in particular in the aftermath of recent blackouts. Even though a high boost TCSC has the capability to perform power flow control, it is often a better solution to subdivide the capacitor branch into a chain of series connected thyristor-switched capacitor steps. The outcome is a thyristor-switched series capacitor (TSSC). This can be seen in the right-hand part of [6].

For a power flow control application, it is natural to compare the TSSC with a PST (Phase Shifting Transformer). Whereas the PST is adequate for handling thermal limitations, it is too slow to mitigate phenomena occurring in the transient period. Furthermore, it has a deteriorating effect on the voltage profile, both in the short and long time perspective, and reduces angular stability in some cases.

The TSSC on the other hand is fast enough to act decisively to mitigate the transient phenomena, and can support voltages both in the perspective of short and long timeframes. However, whereas the PST can both increase and decrease the power flow on the path in which it is installed, the TSSC can only increase the flow. Furthermore, as a rule of thumb, the reactance of a TSSC should be limited to roughly 60 percent of the reactance between the two substations on each side of the TSSC. Thus, if the required

power flow control capability is large (depending on the network topology) the TSSC solution may not be adequate.

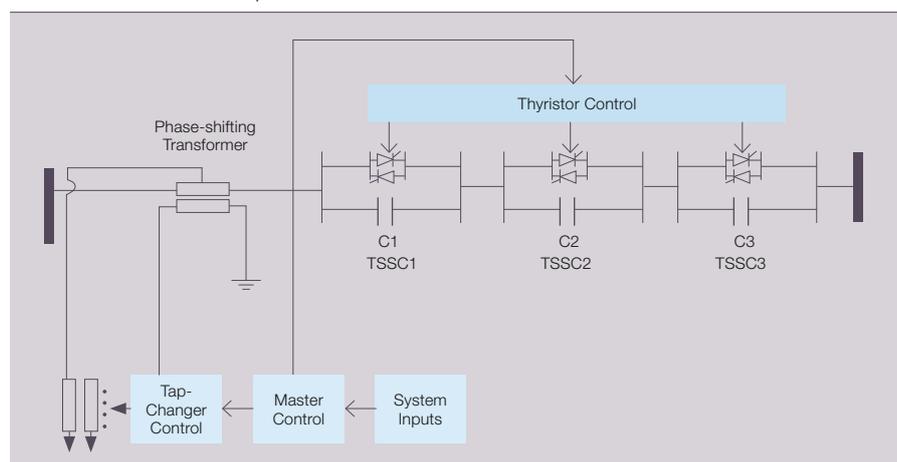
#### Dynaflow

For the purpose of relieving congestion in areas where combinations of control objectives are of concern, ABB is developing a power flow control concept called Dynaflow. It consists of a PST in series with a multi-step TSSC with coordinated control [6].

Clear and transparent mechanisms for sharing responsibilities between system operators are advantageous for successful implementation of corrective control actions.

The total power flow control capability is divided between the PST and the TSSC, resulting in a smaller PST and TSSC. Dynaflow combines the positive qualities of both devices. It is thus capable of performing loss minimization and/or loop flow control in the pre-disturbance period, improving first swing stability, power oscillation damping and/or voltage performance in the transient period and supporting voltages and/or thermal limitations in the post-disturbance period. The control system and the necessary input signals for control are customized for the particular bottleneck to which it is

[6] Schematic configuration of Dynaflow – Dynaflow consists of a phase shifting transformer in series with a multi-step TSSC with coordinated control.



## Powering the economy

applied. The introduction of high performance communication and measurement systems provides a basis for additional performance.

A typical application of Dynaflow would be in relation to city infeed. Highly populated cities are often characterized by having large consumption of active and reactive power while the generation sources are remotely located. This frequently has the consequence that the transmission lines feeding the city are heavily loaded and that dynamic reactive power resources are lacking.

A typical critical disturbance would be a line fault followed by a permanent disconnection of the faulted line. Assuming that the power flow would be unevenly distributed on the remaining transmission paths, and Dynaflow is installed on the path designed to pick up more load in order to avoid overloading the parallel paths, the sequence of control objectives could be as follows:

- In the pre-disturbance period, focus is on minimizing active system losses. A set-point would typically be obtained from a control center possibly based on an optimal power flow calculation.
- Immediately following the fault, all capacitive steps are switched in for the purpose of supporting a voltage recovery. This is particularly important for cities with a considerable proportion of electrical motor loads (eg in the form of air conditioning units). Without voltage support these units would have a tendency to stall and so become a significant drain on reactive power; this in turn can result in local voltage collapse and cascading outages.
- Once voltages have recovered, the control objective would shift to thermal limits. By combining the capability of the PST and the TSSC, power flow is controlled to avoid overload in the path in which the Dynaflow is installed or in parallel paths. Furthermore, if the initiating events are so severe that the overload cannot be completely removed, power flows can be distributed to give the operator as much time as possible to take remedial actions. This would typically imply that the

overload is evenly distributed between the parallel paths.

### WAMS and WACS

A corrective control scheme with the capability to perform dynamic power flow control taking also parallel paths into consideration generally requires that remote measurements are available. Recent advances in the fields of Wide Area Measurements Systems (WAMS) and communications, together with FACTS, open up new possibilities for such Wide Area Control Systems (WACS). Situations with several dynamic power flow control devices installed on parallel paths would in addition require a coordination of the control efforts.

For the purpose of relieving congestion in areas where combinations of control objectives are of concern, ABB is developing a power flow control concept called Dynaflow.

### Related issues

There are obviously limits to what can be accomplished with controllable devices. These limits will determine the new level of power transferred across a transmission interface. From an operational planning point of view it will become important to have efficient security assessment tools, permitting full advantage to be taken of the installed devices.

For historical reasons, bottlenecks are often found on the interface between different grids. Clear and transparent mechanisms for sharing responsibilities between system operators are typically advantageous for successful implementation of corrective control actions.

### Conclusions

FACTS include a portfolio with controllable devices that can relieve congestions and improve the efficiency of the existing network. The exact type to be selected is determined by the nature of the bottleneck. There are often different options. This article presents STATCOM with Energy Storage, TCSC,

as well as Dynaflow as three viable options for congestion relief.

The application of corrective control will in many cases benefit from the application of advanced information and control systems customized for the particular bottleneck.

It is important that operation planning is provided with efficient security assessment tools such that full advantage can be taken of the installations. This is in particular important when handling congestions on the interface between different systems.

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# Breaking news

Ultra-high-voltage switchgear to power China

Walter Holaus, Fredi Stucki

China is in urgent need of electrical power. Huge power plants are built all over the country and the enormous flow of electrical power to the large megacities has to cross several thousand kilometers from the source to the end user.

At those dimensions, losses of the power lines can be significant. The State Grid Corporation of China (SGCC) is thus aiming for 1,100 kV as the voltage level for AC transmission to keep losses as low as possible, a step into a new area of electrical grids.

ABB, together with its partners and suppliers, has developed the heart of such a system – a gas-insulated switchgear design – that could pass all the tests with this groundbreaking technology.

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## Powering the economy

Reliable supply of electrical energy is one of the backbones of modern economies. Its safe and reliable operation mainly depends on high-voltage switchgear – the core part of an electrical power system. The high-voltage circuit breaker in this switchgear is often the last line of defense when big systems must be protected in the event of a short circuit.

Electrical grids and the corresponding substations are well known as air-insulated systems in which the high voltage is kept away from both the ground and people by distances of tens of meters.

Another much more compact way of building high-voltage switchgear is the gas-insulated design – gas-insulated switchgear (GIS) **Factbox 1**.

### GIS technology was introduced to the market in 1966 with the first 170 kV GIS underground substation delivered to the Zürich city center.

GIS technology was introduced to the market in 1966 with the first 170 kV GIS underground substation delivered to the Zürich city center **1**. In 1976, ABB delivered the first 500 kV GIS to Claireville, Canada. With the installation of the first 800 kV GIS in South Africa in 1986, ABB has proven its technology leadership also at the ultra-high-voltage (UHV) level **Factbox 2**. This so-called alpha substation has been in operation for more than 20 years without any failures or unplanned interruptions. The 500 kV GIS in Itaipu, Brazil is still the world's largest installation but will soon be overtaken by the ABB GIS inside the Three Gorges Dam in China.

#### China and innovative GIS technology

China is a huge country where electric power generation happens mainly in the western parts and load centers are typically found in the coastal region – thousands of kilometers apart. Both AC and DC UHV systems are necessary to handle the increase in electric energy consumption and to back up the existing transmission system [1,2].

The State Grid Corporation of China (SGCC) – one of ABB's biggest customers – began designing an AC system with a rated voltage of 1,100 kV a few years ago [3]. This project initiated extensive research and development efforts in research institutes and at equipment manufacturers [4]. To

finally determine the technical feasibility, a group of three Chinese and two Japanese GIS manufacturers and ABB were asked by SGCC to take part in the development of UHV GIS equipment for the Chinese UHV AC demonstration project. It was established in 2008 in central China and

#### Factbox 1 Gas-insulated switchgear (GIS)

Gas-insulated switchgear is widely used in high-voltage transmission and distribution systems. ABB is the leading supplier of GIS at transmission voltage levels. ABB GIS products range from 72 kV up to 800 kV rated voltage with rated currents up to 4,000 A and a short-circuit current switching capability up to 63,000 A. GIS is used in indoor and outdoor applications. The functions provided by GIS are switching, disconnecting, earthing and measuring. As a system with many

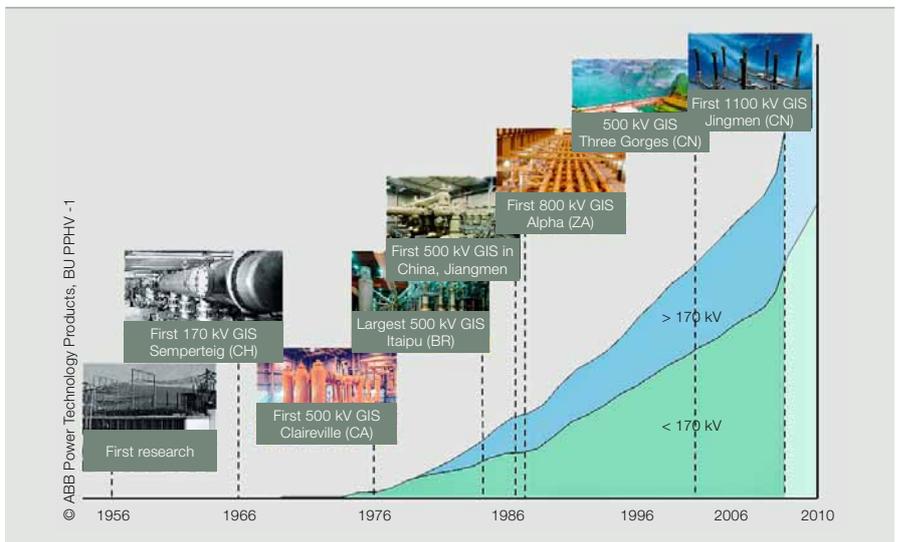
components, each GIS is optimized for the required application. GIS components have a coaxial design with an inner and outer conductor, filled with sulfur hexafluoride (SF<sub>6</sub>) gas at several hundred kPa overpressure. They are connected to each other by bolted flanges – this is why GIS looks like pipelines from outside. Substation designs are called “hybrid GIS” if parts of it (eg, busbars or connections to overhead lines) are air insulated.

#### Factbox 2 Ultra-high voltage (UHV)

Electric power systems are operated at different voltage levels to optimize transmission efficiency, minimize electrical losses and material consumption, and maintain maximum operational safety. The IEC standards provide standardized voltage levels up to 800 kV. Systems operated at a rated voltage above 550 kV are called “ultra-high-voltage” systems. They are used when several thou-

sand MW of electric energy have to be transmitted over hundreds of kilometers. As transmission losses are comparably lower at higher voltages, a step from 550 kV to 1,100 kV reduces the losses by a factor of four. Therefore, UHV systems are especially suitable to efficiently transport bulk power over large distances.

**1** ABB's GIS history: from first research projects to the world's largest installation within 50 years



consists of almost 600 km of high-voltage lines and three substations – Jingmen, Nanjang and Jing Don Nan.

The Chinese UHV AC demonstration project consists of almost 600 km of high-voltage lines and three substations – Jingmen, Nanjang and Jing Don Nan.

### ELK-5 UHV GIS development project

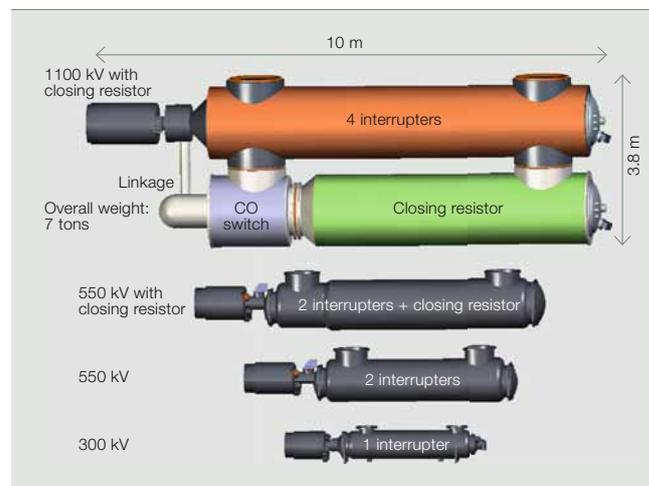
To design and install this 1,100 kV GIS, ABB and Xian Shiky, the biggest Chinese supplier of GIS, established a joint development project called “ELK-5” (ELK is the name of ABB’s GIS systems; 5 indicates the new performance level). The focus for ABB in this joint effort was on the overall design of the hybrid GIS and on the production and shipping of core components, while Shiky focused on production of all other components, type testing – under supervision of SGCC and KEMA experts – and the assembly and installation of the switchgear at Jingmen. A very demanding schedule was set by SGCC – after its start in November 2006 the first installation at Jingmen was to be energized by the end of 2008. Accomplishing this in two years would be a world record for upgrading a GIS to a new, demanding voltage level, during which time the development, verification, type testing, production and installation would also occur. To meet this challenge, ABB assembled a project

team with up to 20 specialists and provided priority access to other experts and test facilities.

### Doubling the voltage level

The insulation performance of GIS depends on many parameters – the gas pressure, the electrode geometry, the voltage-pulse form applied and the polarity or the purity of the SF<sub>6</sub> gas, to mention a few. Even though many of these parameters have been studied as a function of the electrical field strength, phenomena can change significantly in different field configurations. The crucial factor in the GIS design for a new voltage level therefore is the understanding of the various voltage-dependent physical phenomena of electrical insulation. Specific scaling rules have to be applied for every individual component and finally to the whole system. Of special interest are the effects that gain importance at high voltage levels, eg, the so-called very fast transients (VFT) that occur when operating a disconnecter.

2 Dimensions of ABB circuit breakers from 300 kV to 1,100 kV



An especially challenging task is to find the optimal gas pressure for this very high voltage level. There is a trade-off between parameters with positive and negative pressure influence on the insulation performance. ABB studies concluded that a rather small SF<sub>6</sub> gas pressure is best suited for UHV GIS components.

Robustness of the design and operational availability are also key points. Therefore, the following design rules were applied to the UHV GIS design:

- Single phase encapsulation for interrupters
- Separate compartment for closing resistors
- Safe margins for all electrical parameters

The enormous dimensions of the 1,100 kV switchgear require extensive mechanical calculations. Scaling of mechanical parameters, eg, drive energy, speed of contacts or bursting pressure capacity are also very non-linear. In fact, such a development project requires at least as many mechanical engineers as electrical engineers.

All mechanical and electrical design was carried out with true 3-D calculation tools and, whenever possible, proven manufacturing processes were chosen.

### Circuit breaker – the core component

The circuit breaker is a switchgear component capable of safely turning on and off under all switching conditions, such as normal operation or fault clearance. Its operation is accomplished within 50 milliseconds after triggering.

The 1,100 kV circuit breaker is an extension of ABB’s existing circuit-breaker portfolio. It consists of two tanks – one for the interrupters and one for the closing resistor. The interrupters and the CO switch that inserts the closing resistor are both operated by a single spring-hydraulic drive, which has been specifically developed

3 The ABB GIS circuit breaker with the drive unit during assembly in the factory



## Powering the economy

by ABB for this application [5, 6, 7]. A comparison of ABB's circuit breakers for different voltage levels is given in 2. The rated values of 1,100 kV, 4,000 A correspond to a rated power of 7,600 MW for the three phases. This is more than the average electric power consumption of Switzerland.<sup>1)</sup> With this rating the circuit breaker would be capable of turning on and off the electrical power of Switzerland.

The total weight of this modern UHV circuit breaker is only 7.5 tons due to the optimized number of interrupters and the aluminum enclosures 3.

Since it was the world's first equipment rated at 1,100 kV, it had to be tested according to international and Chinese standards; the equipment suppliers and especially the test laboratories thus faced big challenges. Type testing for the circuit breaker was accomplished at Xihari test laboratories in Xian and at ABB in Switzerland 4.

Huge efforts were required to perform the power tests in Xihari at the 1,100 kV level. The most demanding topics were:

- Manufacturing and testing required the intercontinental transport of UHV equipment. Airfreight of complete circuit breakers and other equipment was required to meet the tight schedule of the project.

- Extensive space requirements for the laboratory: The combined voltage tests needed two bushings at a distance of more than 13 m, with each of them a distance of more than 10 m to the laboratory walls.
- The power-switching tests were mostly performed on one-half of the circuit breaker only, as no sufficiently high voltage was available to stress the full-size breaker. This so-called half-pole testing requires a specific enclosure and voltage grading calculations.

As a result of the careful design and manufacturing, the circuit breaker could be successfully tested during the first test series.

### The UHV GIS disconnecter

The basic function of a disconnecter is to disconnect parts of the GIS to safely do maintenance work on the disconnected and earthed parts.

The focus for ABB in this joint effort was on the overall design of the hybrid GIS and on the production and shipping of core components.

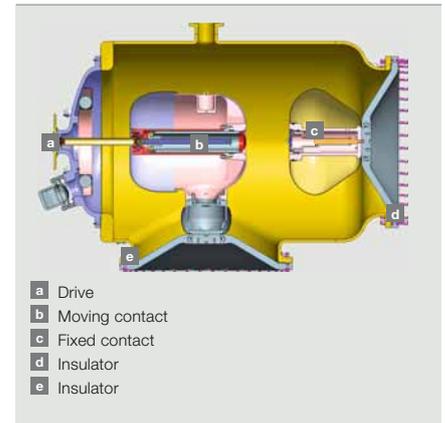
Compared with a circuit breaker, it may operate rather slowly within a few seconds. ABB's 1,100 kV discon-

necter is designed in a 90-degree setup with a visible gap of the inner conductor of less than 300 mm. This gap can withstand more than 3,400 kV

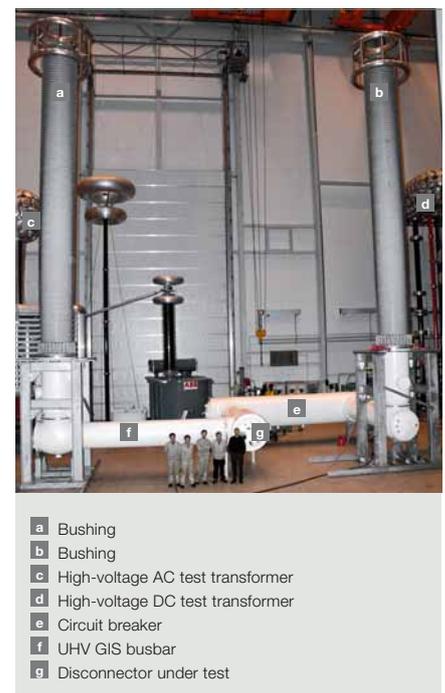
**Factbox** Ratings specified for the 1,100 kV GIS demonstration project

■ Rated voltage	1,100 kV
■ Rated lightning impulse voltage	2,400 kV
■ Rated equipment current	4,000 A
■ Rated busbar current	8,000 A
■ Rated short-circuit current	50 kA

5 Cross-section of the UHV disconnecter



6 Arrangement for disconnecter switching tests at the STRI laboratory



4 Development team and test pole for the 1,100 kV circuit breaker at Baden Power Lab (Switzerland) after T100s test



during high-voltage testing. It is one of the clear advantages of an SF<sub>6</sub> GIS design: to insulate very high voltages across small distances. Exposing conductors in open air to 3,400 kV would require a minimum clearance of 13 m to prevent flashovers.

The disconnecter switching type tests were performed at the Swedish Transmission Research Institute (STRID) in Ludvika, Sweden, the only lab with corresponding facilities [5] [6]. The comparably slow operation of a disconnecter leads to sparking during closing and opening in the contact gap. These sparks generate the very fast transients (VFT) that propagate through the GIS, a phenomenon that puts the highest EMC (electromagnetic compatibility) requirements on the components undergoing the test.

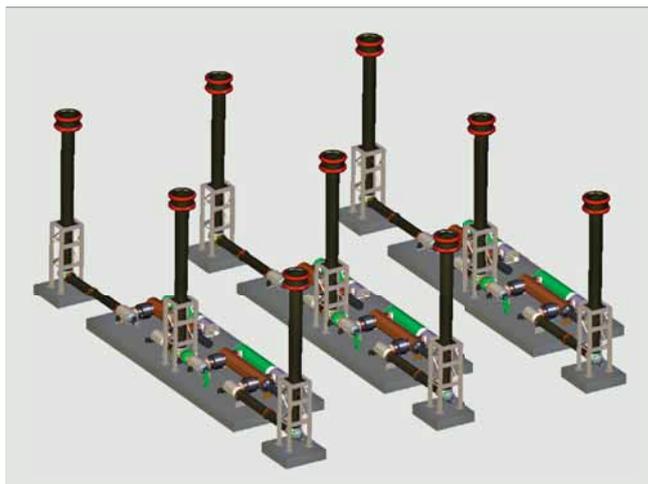
#### The first UHV GIS substation

After development and the successful type testing in 2007 and of 2008, ABB and Shiky began to assemble and ship the first equipment to the substation at Jingmen. This substation includes an almost complete set of GIS components, such as circuit breakers with closing resistors, disconnectors, earthing switches, current transformers, busbars, bushings and insulators [7].

Extensive layout studies to find the optimum arrangement of the GIS components proved that a “flat” setup with good accessibility would be best suited for the Jingmen hybrid GIS substation [8]. The layout has the following characteristics:

- All GIS switching equipment is placed close to ground level.
- The flat arrangement improves robustness against seismic stresses.
- All the drives are placed at a height within 1.5 m of the ground, which provides convenient and safe access for operators during installation and maintenance.
- No platforms or ladders are needed.
- The layout can be easily extended in the busbar direction.
- It requires a minimum of steel construction as a bay structure.

7 Layout of the Jingmen 1,100kV hybrid GIS substation



- The on-site workload is small and allows for fast installation.

The substation was installed in 2008 near the city of Jingmen in Central China. It will transmit part of the energy produced by the Three Gorges power plant to the northern part of China.

#### Meeting the challenge

The ELK-5 development project was a big challenge in many respects: a pioneering design in an unprecedented execution time and a cross-continental cooperation with suppliers and partners in Europe and China, who with very different cultural backgrounds worked closely together.

Type tests of the ELK-5 components were carried out simultaneously in

Chinese, Swedish and Swiss laboratories. This project was not only the start of a new era in ultra-high-voltage transmission but also a powerful demonstration of the combined engineering capabilities of the world's technology leaders.

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#### Footnote

- <sup>1)</sup> 5th Annual Report of SwissEnergy 2005/2006.  
[http://www.bfe.admin.ch/energie/00556/index.html?lang=en&dossier\\_id=01060](http://www.bfe.admin.ch/energie/00556/index.html?lang=en&dossier_id=01060)

# Small footprint, high performance

Design of an air-insulated switchgear substation based on new technology

Lei Jing, Hans-Erik Olovsson, Jianzhong Fan, Richard Thomas



As cities grow, so does their hunger for electrical power. To achieve the necessary bulk transmission, the highest voltage level of a city's power supply is continuously changing: from 110 kV to 220 kV, even reaching 500 kV in some mega-cities in China and other countries. This calls for extra-high-voltage (EHV) substations to act as load hubs in the city. However, such developments lead to a conflict between substation footprint and power requirement. In general, the higher the voltage level, the more power a substation handles and the larger the area it needs. Such demands, however, conflict with typical limitations that are prevalent in city areas. The shortage of land is the most important among these and the huge investment cost is also a very serious challenge. Furthermore, as an energy distribution center for very many people, such a substation must perform with high reliability and availability. All this underpins the case for a compact substation, featuring smaller footprint while reduced customer costs and a maintaining high availability.

Today's technology is making these objectives attainable. Firstly, new primary equipment permits a drastic reduction in the footprint area. A revolution in circuit-breaker design led by ABB is allowing switchgear configuration or even integration to be redefined, decreasing costs both in terms of land acquisition and equipment cost. Secondly, innovative optical sensors are replacing the traditional expensive and large current transformers (CT). These non-traditional CTs are so small that they can be easily integrated with the breaker in the same circuit. Thirdly, the use of such sensors is an integral aspect of a digital substation. This not only enhances substation performance, but also saves on investment, eg, cables for secondary instrument transformer circuits and for the control of circuit breakers, disconnectors, and earthing switches.

In an urban substation, the key factor is land-related cost.

#### Traditional air-insulated substations

Utilities must meet huge construction and installation costs when investing in a substation. Obviously, primary equipment, such as transformers and circuit breakers, are very expensive, especially when these are for extra high voltages. Further, the substation automation system (SAS) is itself cost-

ly to install, not only because of the large numbers of intelligent electronic devices (IED) and computers, but due to the extensive cabling for measurement and control.

However, in an urban substation, the key factor is land-related cost. The purchase is an integral part of this process, but is only the last step. Unlike general commodities, land cannot be obtained with money alone. Safety, environment, and noise are all factors to be considered in the approval of a substation. The smaller the plot of land, the less impact a substation has on its surroundings.

**1** shows the single-line diagram (SLD) of a 500 kV substation [1]. In this substation, there are six 500 kV diameters (1½ circuit breaker scheme) and twelve 220 kV double busbar bays.

In this substation, all primary equipment is so large that often an area of 60,000 m<sup>2</sup> is used **2**. Obviously, it is difficult to find a suitable location for such an installation in the city.

The fast-increasing power demand, however, makes such substations indispensable. Plans of the Beijing electric power company see a 500 kV double-ring network around the city being completed in 2010. This will feature 10 substations (each for 500 kV and 2600 MW). These include four

load-hub substations located in the city center. The demand for and value of land is so high, that any compact substation solution becomes attractive. One obvious approach is to use gas-insulated switchgear (GIS), which would occupy only 30,000 m<sup>2</sup> for the same SLD as in **1** [1]. This will, however, be more costly than air-insulated substations. According to China State Grid [1], a GIS substation requires around 40 percent higher investment. Therefore, an alternative for the traditional air-insulated switchgear (AIS) substation, with less footprint and customer cost is required.

Safety, environment, and noise are all factors to be considered in the approval of a substation.

#### The technology solution

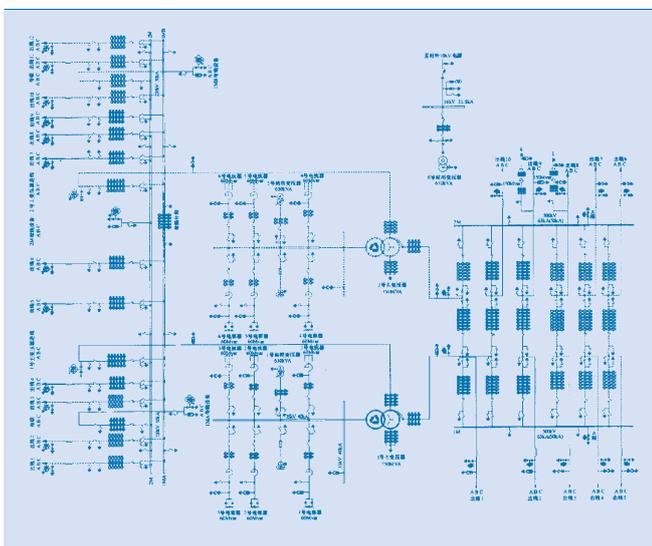
Applying new technologies, ABB can design AIS substations with reduced installation cost and a smaller footprint.

#### New circuit breaker

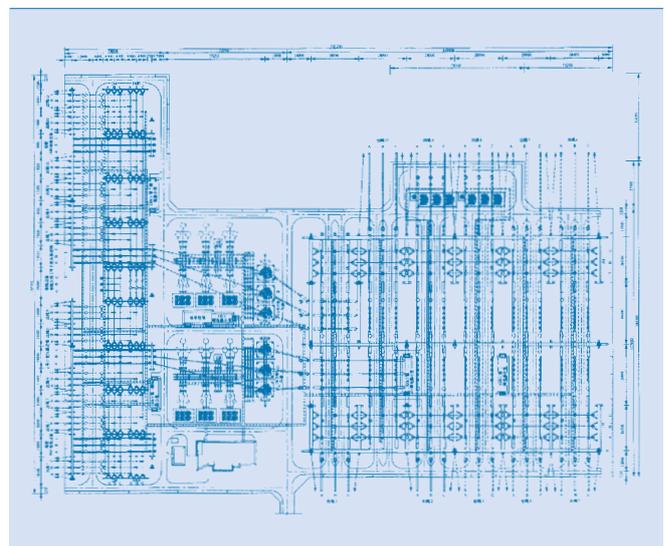
A section view of a 500 kV bay is shown in **3**. The diagram shows that the disconnectors take up most of the space as each circuit breaker needs two disconnectors for safe isolation.

With the modern and well proven SF<sub>6</sub> circuit breakers (CB) of the self blast

**1** Single line diagram (SLD) of a typical 500 kV substation



**2** Layout of a typical 500 kV substation using air-insulated switchgear (AIS)



## Powering the economy

and/or puffer type, ABB now can offer an alternative that provides opportunities to both simplify substations and save space. A new disconnecting circuit breaker (DCB), named “Combined”, has been developed and manufactured [2]. The disconnection func-

tion for Combined is integrated in the breaking chamber. There are no additional contacts or other components for the disconnecting function in the SF<sub>6</sub> breaking chamber. When the circuit breaker contacts are in the open position, they can be mechanically

locked in the open position, fulfilling the disconnecting function requirement and maintenance on adjacent parts of the switchgear or network can be carried out. Further, eliminating the air-exposed disconnector contacts also provides for lower maintenance and higher switchgear reliability. Disconnecting CB requirements are specified in the IEC standard 62271-108 [4].

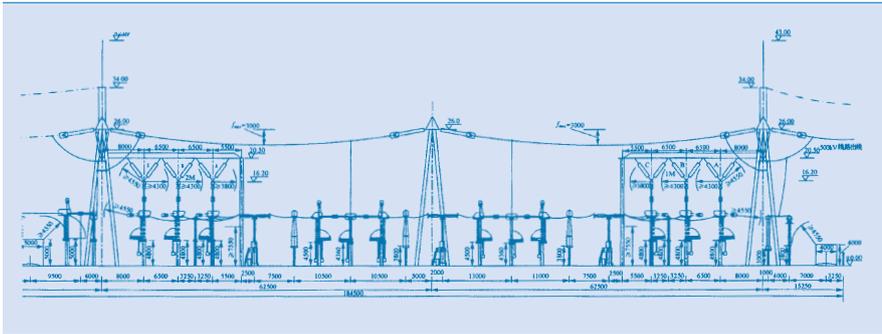
With the modern and well proven SF<sub>6</sub> circuit breakers of the self blast and/or puffer type, ABB now can offer an alternative that provides opportunities to both simplify substations and save space.

DCBs can save not only equipment cost, but also reduce the footprint and related construction costs while increasing availability. A layout comparison between conventional and Combined 145 kV based switchyards is shown in [5].

### Innovative sensors

Besides the disconnector, the traditional CT (current transformer) also occupies a lot of space in [3]. However, new sensing technology makes the alternative solution possible.

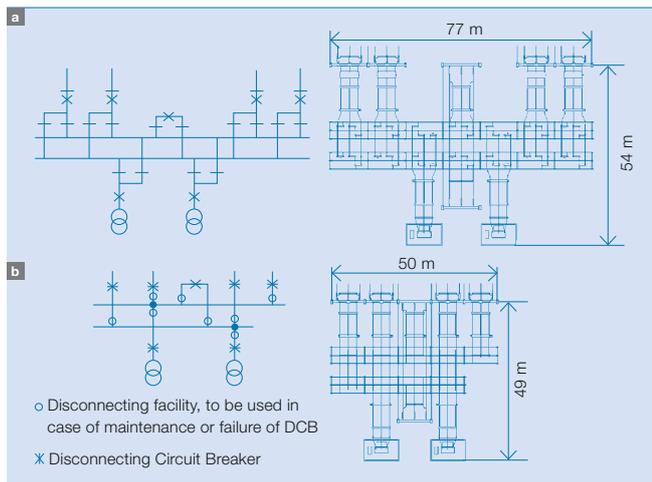
3 Section view of a 500 kV 1½ diameter



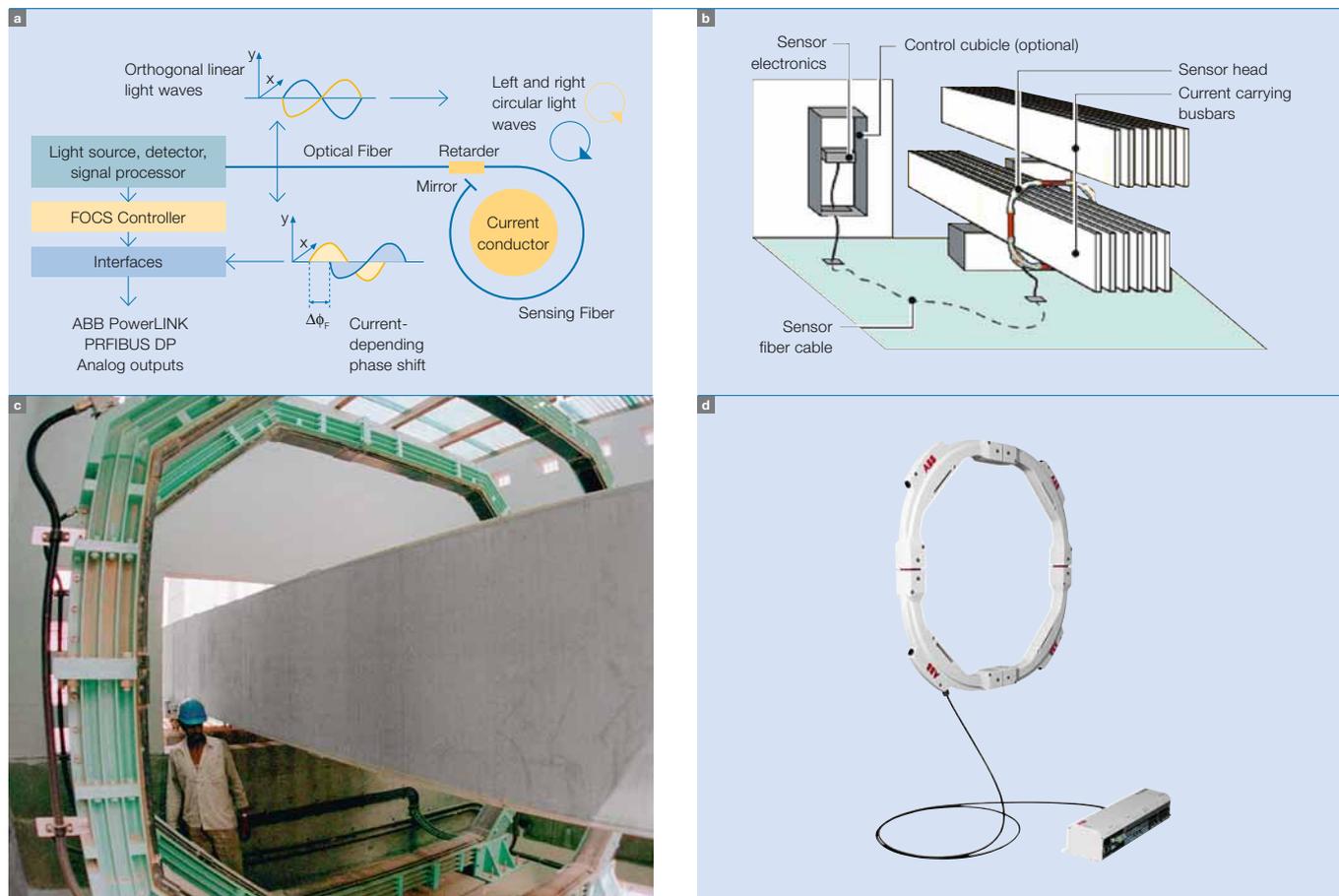
4 Disconnecting circuit breakers with two a and one b breaking chamber



5 Space requirement of 145 kV substation (traditional) a compared to the same functionality achieved with the “Combined” breaker b



6 ABB FOCS measuring principle **a**, installation **b**, two conventional Hall effect dc current transducers for 400 kV **c** and the measurement coil **d**.



Innovative sensors are beginning to replace regular CT in recent years. Fiber-optic current sensors (FOCS) present an excellent alternative [3]. Using the Faraday Effect, FOCS can easily measure the current with a fiber optic loop placed around the conductor. The resulting simple installation is shown in **6**. Another benefit is the smaller footprint compared to the large electromagnetic CT.

Additionally, in respect to digital signal processing, FOCS can interface with process-level devices in a substation automation system (SAS). Consequently, the IEC 61850 process bus (-9-2) concept can be implemented, reducing need of secondary cabling and simplifying construction and commissioning work.

#### IEC 61850-9-2 application

As mentioned above, FOCS can transfer all measured values in digital format. Thus, if a FOCS is applied with an IEC 61850-9-2 compatible merging

unit, the digital values can be transmitted to bay level IEDs via the fiber optic network, replacing the large amount of copper cables. Figure **7a** represents the technical evolution of SA from Process (bottom) up to NCC (top) from conventional (left) to intelligent (right). Figure **7b** shows the architecture of IEC 61850 based SAS, which is the concrete implementation of the intelligent system in Figure **7a**. For a three-phase power line, at least three groups of measuring cables are eliminated with the intelligent system. Furthermore, as there is no magnetic saturation in FOCS, one set of FOCS can be used for both monitoring and protection, or even metering. In this way, further cabling can be saved.

Moreover, if an intelligent breaker IED, compatible to IEC61850-9-2, is designed and embedded in the circuit breaker, the control will use the same fiber-optic network with current and voltage sensing function. The control

cable is then also replaced by the network, resulting in a more reliable and cost optimized SA system.

#### Layout reconfiguration and optimization

Based on the new technologies above, the substation footprint can be reduced by more than 50 percent, while at the same time increasing its availability and reliability.

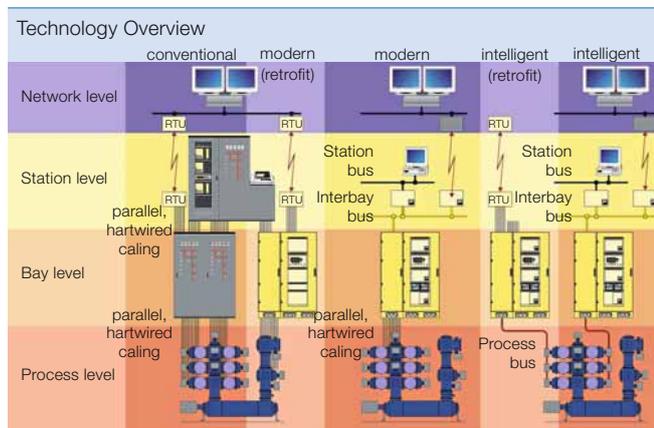
Using the Faraday Effect, FOCS can easily measure the current with a fiber optic loop placed around the conductor.

Moreover, the use of DCB not only permits the disconnecter to be eliminated, but also allows the busbar topology to be improved. Since the maintenance interval for a Combined DCB is 15 years, the replacement of double by a sectionalized single bus-

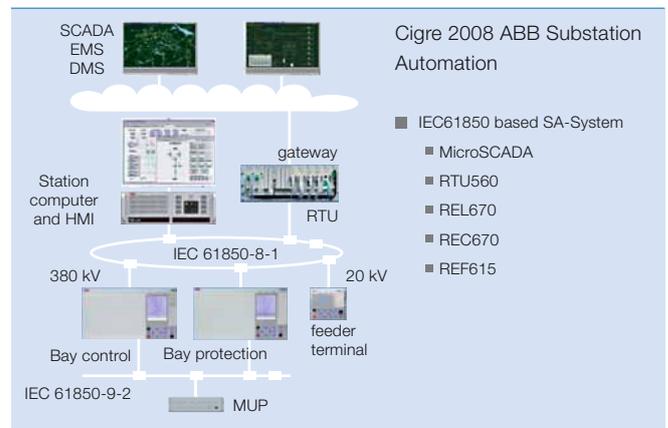
## Powering the economy

### 7 Digital substation configuration

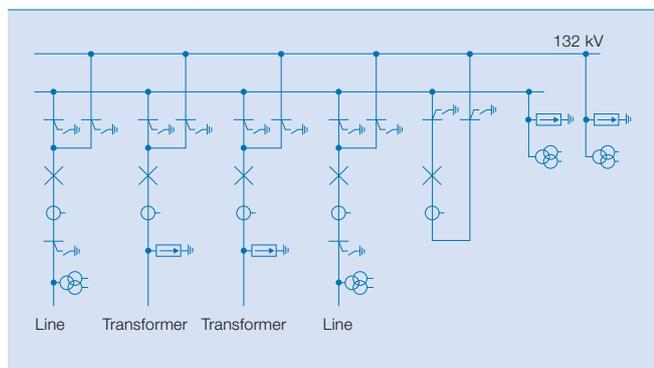
#### a SAS evolution



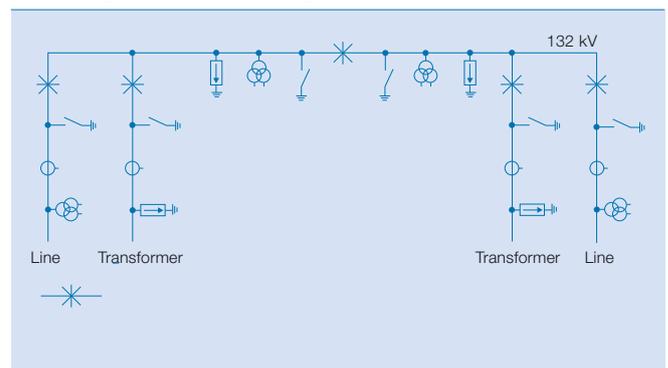
#### b IEC 61850 based SAS



#### 8 Traditional switchgear layout with disconnectors and circuit breakers



#### 9 Switchgear with disconnecting circuit breakers (DCB)



bar system is justified without availability being compromised. Comparing the layouts in 8 and 9, it can be seen how busbar and related disconnectors are eliminated, simplifying the layout.

The use of a combined disconnecting circuit breaker as primary equipment opens the opportunity for greatly improved efficiency in substation construction, operation and layout.

In addition, because FOCS and an intelligent interface are used, the cable and related auxiliaries can be done away with, resulting in a much simplified control setup and simplifying connections to the primary equipment.

#### Switching ahead

An air insulated substation can be designed to be more reliable and cost efficient by introducing new equipment and technologies. The use of a combined disconnecting circuit breaker as primary equipment opens the opportunity for greatly improved efficiency in substation construction, operation and layout. The innovative current sensor together with an intelligent interface enables the implementation of the IEC 61850-based process bus protocol.

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# Performing at a higher level

Advanced heat pipe cooling increases circuit breaker performance by over 25 percent

Daniel Chartouni, Martin Lakner, Giosafat Cavaliere



A generator circuit breaker (GCB) is a core component of a power plant, protecting both the generator and the power transformer. ABB's current breaker portfolio includes breakers with rated nominal currents ranging from 6300 A to over 50,000 A. HECS breakers are designed for nominal currents up to 18,000 A. However, a side effect of these large currents is heat dissipation in the device, which must be limited if other system components are to remain within their rated temperature tolerances. Natural cooling limits the rated nominal current and therefore many of today's GCBs employ forced cooling methods to increase nominal current levels. However, these "forced" coolers also limit nominal current capability.

To increase GCB nominal currents, an innovative cooling method was required to meet the ever-increasing demand for lighter, cheaper and more powerful devices. Using so-called heat pipes to achieve efficient heat transfer, not only have they developed two products that are lighter and more robust than previous versions, but GCB performance has increased by over 25 percent!

## Powering the economy

Power devices are following the trend of most other electrical products by becoming smaller and lighter while at the same time incorporating greater functionality. Cost efficiency is for the most part the main driving force behind this because a lighter device results in lower material, transportation and installation costs. One part of ABB's Generator Circuit Breaker (GCB) family **Factbox 1**, the HECS breaker, has gone through this process with impressive results: by replacing a so-called "forced" cooling system (ie, one that needs pumps, fans or motors to operate) with a "passive" cooling apparatus (one that operates without the need for pumps, fans or motors), nominal HECS breaker current has been increased from today's 18,000 A to 23,000 A! Using an innovative approach based on a heat pipe cooling concept, ABB engineers have transformed members of this family of devices into silent, slimmer and lighter versions of their former selves with extremely low-maintenance requirements **Factbox 2**.

Efficient heat transfer in ABB's HECS circuit breakers demanded a purely passive and low-maintenance device if nominal current values were to be increased.

### Knowing what to do

Nominal and short-circuit currents generate a tremendous amount of heat. Even tiny electrical resistances (resulting from the material or sliding electrical contacts) lead to ohmic losses, which can generate many kilowatts of heat. However, the steady-state temperature at the hot spot has to be limited to 105 °C<sup>1)</sup> during normal (closed) operation, thereby thermally limiting the maximum allowable nominal current. Hence, the operating temperature of the generator circuit breaker is determined by both the nominal current and the cooling of the device. To successfully increase the rated nominal current of its GCBs, engineers had to focus on the thermal management of the GCB.

### Factbox 1 ABB's Generator Circuit Breaker (GCB) portfolio

ABB's GCBs are widely used in all kinds of power stations, such as gas turbine, combined cycle and thermal power plants, as well as geothermal, hydro and pumped storage power stations. Currently the company has a market share of some 70 percent. The breaker portfolio covers devices with electrical power ratings from 100 MVA to over 1500 MVA. Included are breakers with rated nominal currents ranging from 6300 A (and a maximum short-circuit current of 63 kA) to over 50,000 A (with a short circuit current rating of 210 kA). Introduced in 2003 and available for both indoor and outdoor application, HECS-type breakers are rated for the power range up to 800 MVA. They can switch short-circuit currents up to 130 kA and are suited for nominal currents of up to 13,000 A using naturally cooled



systems and 18,000 A with forced cooled systems.

The power density is very high considering their small size and weight – typically 6000 kg. They are therefore ideal for retrofitting in existing power plants, and allow substantial savings in transportation and installation costs.

### Factbox 2 Overview of the new products resulting from heat pipe implementation

New product name	Maximum operating current	
	Today's HECS-based product	New product with heat pipe (passive cooling)
HECS-100/130XLp	18,000 A (with forced cooling)	18,000 A
HECPS-5Sp (pump storage solution)	13,500 A	18,000 A
HECS-130XXLp	Not available	23,000 A

Within ABB's HECS breaker family, nominal currents of up to 13,000 A are possible using natural cooling methods. However, a forced air-to-air cooling device – itself a heat generator as well as a source of extra weight – is required to increase this value to a maximum of 18,000 A. Increasing the nominal current of a given breaker to 23,000 A can therefore be achieved only by improving the heat transfer from the HECS conductor to the environment while at the same time ensuring that the temperature of sensitive components stays within a tolerable range. This challenge was made even more taxing given that the heat source (the conductor) is on a high electrical potential of 25.3 kV while the heat sink (the HECS enclosure) is ground-

ed, and any form of forced cooling has undesirable side effects. If efficient heat transfer across this large electrically isolated gap was to be achieved, a purely passive and low-maintenance device was needed. And such a device was realized using heat pipes<sup>2)</sup> **Factbox 3**.

### Product development

Even though it has been around for several decades, the heat pipe con-

#### Footnote

<sup>1)</sup> The IEEE standard allows a temperature increase of 65 K for silver-coated contacts above an ambient temperature of 40 °C.

<sup>2)</sup> The principle of the heat pipe has been around for several decades, and cooling systems in the consumer electronics industry use the idea.

**1** A single pole of a heat pipe cooled HECS breaker. From the outside, only the condenser fins are visible on the upper section of the encapsulation



cept was never applied to GCB cooling because of the challenge of using electrically insulated heat pipes where a large potential difference exists between the heat source (the evaporator) and sink (the condenser). This in turn ruled out a design composed entirely of metallic components, requiring instead a solution that provides mechanical robustness and material compatibility between the heat pipe materials and the working fluid. Overall, the following requirements for a successful solution needed to be met:

**Thermal management**

The maximum total heat load to be transferred is determined by the current and the resistances in the circuit breaker. The number of heat pipe systems therefore determines the maximum allowable thermal resistance for the individual components.

**Heat pipe dielectric design**

This refers in particular to the dielectric insulation between the conductor and the enclosure for normal operating conditions (namely around 25 kV) and for other voltages the system needs to be protected against, for example those generated by lightning impulses. The solid insulators of the heat pipes as well as the working fluid must also comply with this requirement.

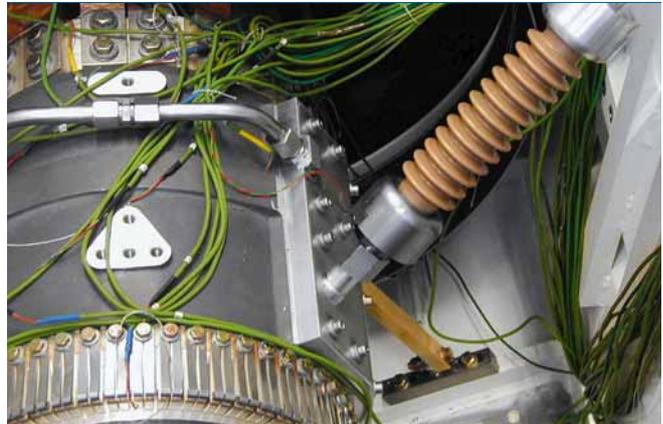
**Heat pipe mechanical design**

The system must be able to tolerate a high number of switching operations (20,000 cycles), transport and earthquakes.

**Long term stability and environmental considerations**

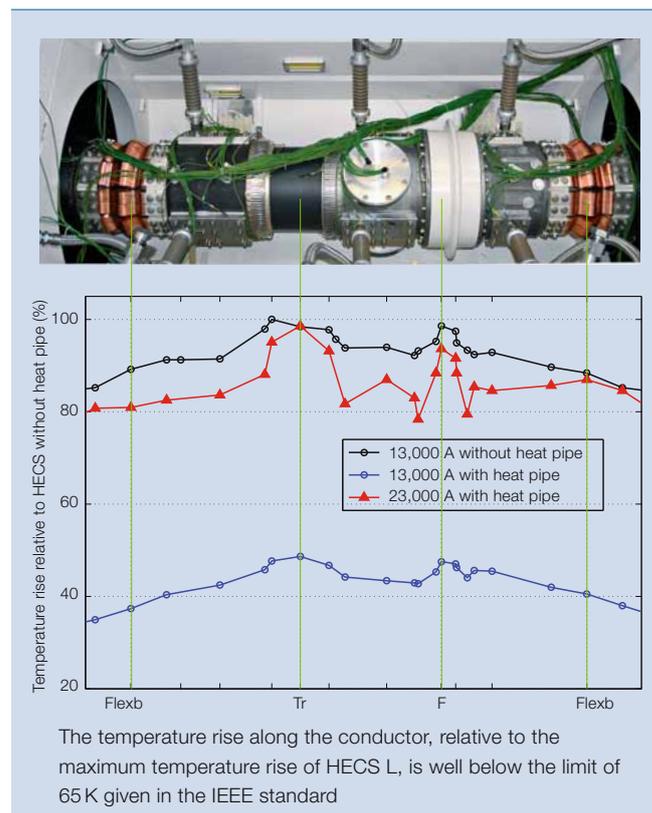
The system needs to be maintenance-free for over 20 years. In addition, the

**2** Evaporator and isolating section attached to the connection chamber. The vapor flows through the waved insulating tube to the condenser (see **3**)



working fluid needs to be environmentally friendly for at least 20 years. Environmental protection requires low global warming and ozone-depletion potential. The LCA (Life Cycle Assessment), which compares the novel cooling device to the current forced air-to-air cooler, needs to show that the heat pipe solution is indeed more environmentally friendly.

**3** Heat pipes attached to the HECS GCB. The transport sections are connected to the condensers that are incorporated into the enclosure



Using an innovative approach based on a heat pipe cooling concept, ABB's HECS breakers have been transformed into silent, slimmer and lighter versions of their former selves.

**Technical realization**

A standard GCB consists of three parallel phases. Each GCB conductor is housed in an individual enclosure which is insulated from the pole frame **1**. In the ABB design, each phase has six heat pipes, and the heat generated by a nominal current has to be transferred to the ambient through these heat pipes. To do this as uniformly as possible, the conductor area

## Powering the economy

covered by the evaporator was maximized<sup>3)</sup> 2. Homogeneous heat dissipation to the six evaporators is needed to ensure that no hot spots occur inside the conductor material due to the non-vanishing thermal resistance of the material itself. The isolating section actually proved quite challenging in that its dielectric stability had to be ensured, as well as its mechanical integrity against breaker operation, not to mention air and working fluid diffusion<sup>4)</sup>. Results taken during the testing phase are shown in 3. Not only has the nominal current been increased by 27.8 percent, from 18,000 A to 23,000 A, but the measured thermal resistance using the heat pipe solution was 58 mK/W. In other words, the temperature increase for a heat dissipation of 1000 W is only 58 K.

### Looking to the future

ABB's portfolio is the widest available on the GCB market. Upgrading the existing HECS-XL breaker with the

passive heat pipe cooling system, as well as the creation of two new products, HECS-100/130XXLp and HECPS-5Sp, for standard and pump storage applications, will extend this portfolio even further Factbox 2.

**ABB's new heat pipe solution needs no electricity to operate, requires little maintenance and has helped increase circuit breaker performance by over 25 percent!**

The HECS-100/130XL breaker currently uses a forced cooling system. ABB's aim is to keep the market leadership with a substitute for HECS XL. This version would be feasible either with small attached evaporators and smaller number of full-size heat pipe systems. Of the proposed new products, the

HECS-100/130XXLp breaker product is aimed at the market segment between 18,000 A and 23,000 A. The maximum possible evaporator surface has been chosen for this version, guaranteeing a very low thermal resistance and a homogeneous temperature distribution along the disconnecter profile. Another important parameter in this design is the condenser surface area mainly because it influences the thermal resistance along the heat pipe system. Equipping the HECPS-5S breaker – a pump storage solution – with a heat pipe cooling system would extend its nominal current to 18,000 A.

ABB's new heat pipe solution needs no electricity to operate, requires little maintenance and is impressively silent. Its main benefit, however, is the extension of the HECS generator breaker nominal current to 23,000 A. Not only will this new passive cooling solution contribute to further complete the company's circuit breaker portfolio, but it will also allow for a very cost-efficient product for each kind of application. These products will make their market debut in 2008.

#### Factbox 3 Heat pipes as an alternative cooling concept

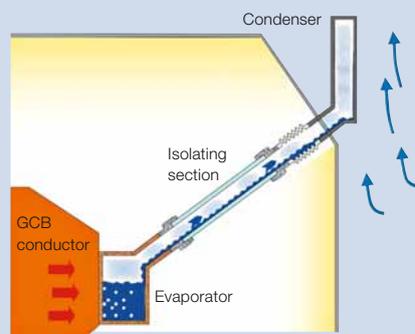
A heat pipe is a device that makes use of the effect that a liquid absorbs heat when it is evaporated (latent heat of vaporization) and that this heat can subsequently be released somewhere else during the condensation process.

The system is composed of three major components: an evaporator section which is attached to the GCB conductor (heat source); a transfer section; and a condenser section located in the cooler environment outside the enclosure.

It operates like a closed-loop system that is partly filled with a working fluid. Inside the evaporator, the heat flux causes the working liquid to boil.

A small pressure imbalance then carries the vapor to the condenser section where the heat is dissipated by natural convection cooling to the outside of the GCB enclosure.

Following the condensation process, the liquid returns to the evaporator via a gravity heat pipe. An outstanding characteristic of



this pipe is that it is driven only by the heat that is being transferred and by the gravity that returns the condensed liquid, making it a purely passive device.

Because the fluid boils and condenses at roughly the same temperature, the temperature gradient along the pipe is small, leading to efficient heat transfer and a heat flux value that may be several thousand times higher than that in good metallic thermal conductors.

The heat flux from the evaporator to the condenser is limited only by the vapor flow properties inside the transport section.

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#### Footnotes

<sup>3)</sup> Doing this also reduces the thermal resistance of the evaporator.

<sup>4)</sup> At the beginning of the project, it was thought that the insertion of an electrically insulating tube, carrying liquid and vapor, between the evaporator and the condenser would be straightforward. However, challenges arose because official type tests needed to be carried out for voltages up to 88 kV AC and 165 kV (lightning impulse voltage). Additionally, the tube has to be mechanically very strong (metal cannot be used), and finally the connection at both ends of the tube to the rest of the pipe must be very tight.

# Chemistry matters

Protecting the environment

Markku Rissanen, Shiwen Zheng

Industries throughout the world have a responsibility to protect the environment from toxic waste. The importance of this effort has never been greater, as millions of tons of chemicals are produced and used by industries worldwide every year. ABB makes every effort to minimize its environmental impact when manufacturing products. With the rapid growth of China's economy and its expanding industrial capacity, ABB China has had a great opportunity to reduce chemical emissions by imposing restrictions on the chemicals used by its suppliers. Initiatives to replace materials with equivalent biodegradable products will further reduce the impact on the environment.



## Productivity

Understanding the complex behavior of chemicals in the environment and the implications they may have on public health is far from easy. Some groups of chemicals have been shown to slowly degrade our environment, contributing to acid rain, global warming or the destruction of stratospheric ozone, while others have more immediate effects on living organisms, such as carcinogens or teratogens.

Each year, ABB manufactures and delivers millions of products and can therefore positively influence chemical emissions in the environment. ABB constantly reviews the materials used in its operations around the world and makes every effort to ensure that the most environmentally friendly materials are used to manufacture its products. ABB China has successfully reduced chemical emissions by imposing restrictions on the chemicals used by companies supplying materials for use in ABB products.

### Reducing VOCs

Volatile organic compounds (VOCs) are characterized by their tendency to vaporize and disperse into the environment. The most commonly occurring VOC is the greenhouse gas methane, but the group includes organic solvents, such as those found in paint and paint stripper, and many other

household chemicals. The main contributor to the production of VOCs in ABB China was the paint used to protect motors and transformers <sup>1</sup>. In 2007, ABB operations generated more than 800 tons of VOCs worldwide, 22 percent (179 tons) of which was generated in ABB China. ABB as a group has successfully reduced these emissions <sup>2</sup> [1].

When painting with water-based paints an 80 percent reduction in VOCs can be made as compared with solvent-based paints.

VOCs are toxic in their own right, but they pose an additional hazard because they react in sunlight with nitrogen oxides to produce ozone. Although ozone plays a positive role in the stratosphere to protect the Earth from excess ultraviolet radiation from the sun, at ground level it can cause respiratory problems.

Already in 2000, ABB took an important step to reduce VOC emissions, requiring its suppliers to stop using benzene, toluene and xylene in the paints they supplied to ABB to coat and protect motors produced at the ABB Shanghai Motor Company Ltd.

The use of solvent-based paints to protect motors is a common practice among motor manufacturers. In 2007, encouraged by this successful initiative, ABB embarked on a factory trial of water-based paints to reduce emissions further still. After six months of testing, in March 2008 ABB was able to replace its solvent-based paints with remarkable results. VOC emissions are reduced by 80 percent when solvent-based paints are replaced by water-based paints. Using water-based paints it is now possible for the motor factory to avoid 20 tons of VOC emissions every year.

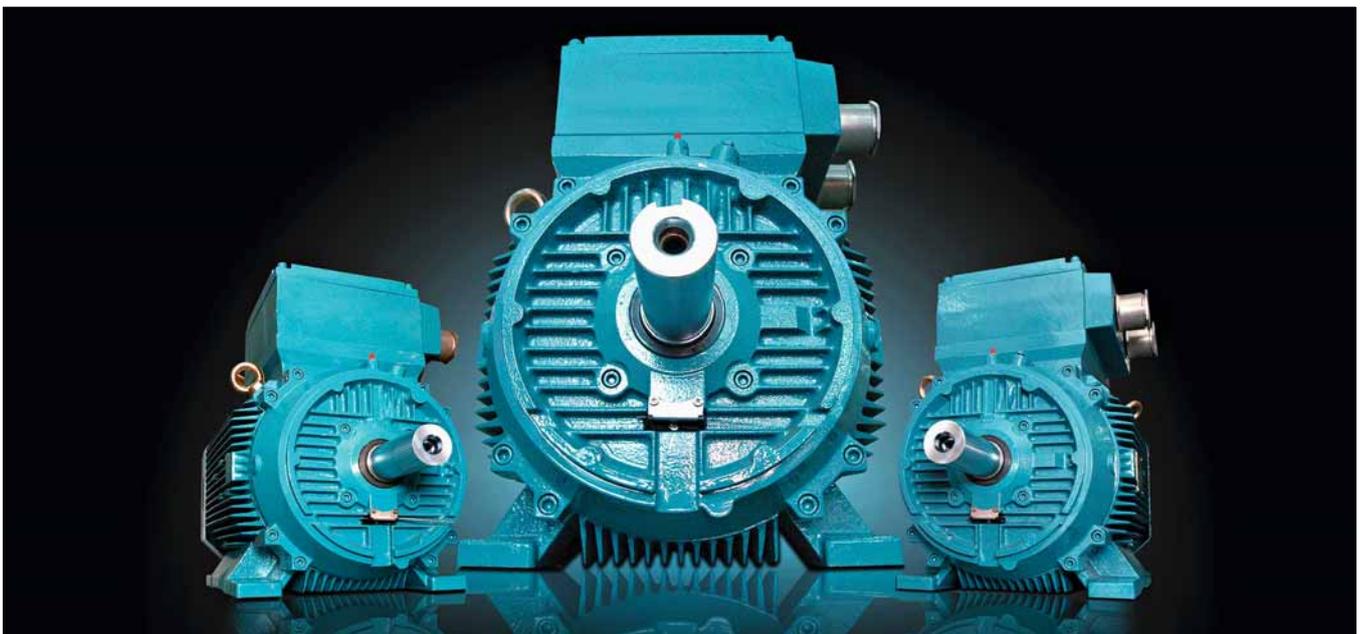
### Replacing POP-containing materials

Another large group of hazardous compounds that can be produced during manufacturing processes are the persistent organic pollutants (POPs). Unlike VOCs, POPs are resistant to degradation in the environment, and because they are so long lived, wind and rain can disperse them over wide

<sup>2</sup> VOC emission reductions

	Y2007 tons	Y2006 tons	Y2005 tons
ABB Group	814	992	981
ABB China	179	261	226
% from China	22	26	23

<sup>1</sup> Motors from ABB Shanghai Motors Company, Ltd



3 Automatic processing system for cable



areas. POPs are fat soluble and so accumulate in the food chain and can ultimately accumulate in humans.

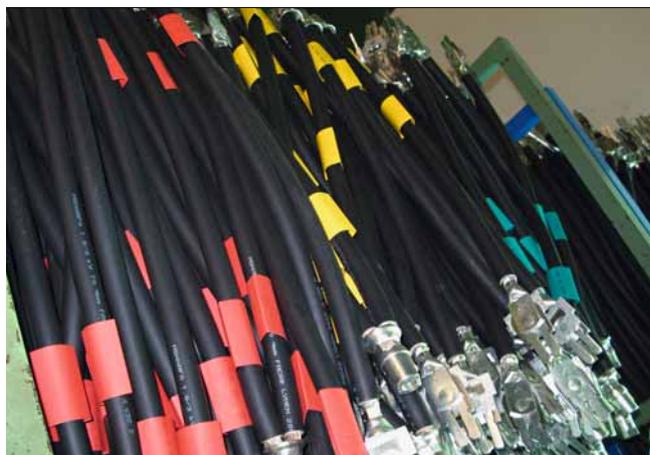
Many chemicals fall into the POP group, including brominated flame retardants, such as polybrominated biphenyl (PBB) and polybrominated biphenyl ethers (PBDE), which are used in the manufacturing of printed circuit boards, computer cases and insulation for polymer cables. The rise in demand for electronic equipment has led to a dramatic increase in the use of such POPs.

Polymer cable insulation is widely used in ABB, and some contains brominated flame retardants 3. These are used at ABB Xiamen Switchgear Company Ltd and ABB Xiamen Low Voltage Equipment Company Ltd. Although there are no regulations in China to prohibit their use, ABB is taking actions to replace cable insulators using brominated flame retardants with more environmentally friendly

5 Careful monitoring of ABB's performance



4 Finished cable for main circuit



alternatives. From September 2007, both ABB Xiamen Switchgear and ABB Xiamen Low Voltage Equipment took action to phase out brominated flame retardants. By the end of May 2008, 25 of 30 suppliers had already removed these substances from their insulated cables 4.

Although there are no regulations in China to prohibit the use of POPs, ABB is taking actions to replace cable insulators that use brominated flame retardants with more environmentally friendly alternatives.

#### Finding alternatives

ABB China is collaborating to phase out hazardous substances and compounds with a negative environmental impact. The process involves theoretical investigations, calculations and material testing. ABB is well equipped to undertake such investigations with experienced staff, knowledgeable in materials, mechanics and chemistry, making tests in

state-of-the-art laboratories. All new materials to be used in ABB production processes are checked to determine if they contain hazardous compounds and to find better alternatives to reduce their environmental impact. For more detailed information about ABB's environmental sustainability program, see "The ABB Group Annual Report 2007." [1]

In addition to these routine tests, ABB is continuously surveying appropriate biodegradable alternative materials with the aim of replacing petroleum-based plastics. As oil prices are increasing steadily, there are also likely to be cost benefits when using renewable resource materials that can be grown locally. To find such bio-based materials and replace old, well-known technology takes time, but these investments lead to great environmental benefits.

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#### Reference

[1] ABB Sustainability Report 2007. Contributing to a better world. [http://library.abb.com/global/scot/scot266.nsf/veritydisplay/8213e927815a7165c1257410003c0c60/\\$File/Sustainability%20review%202007.pdf](http://library.abb.com/global/scot/scot266.nsf/veritydisplay/8213e927815a7165c1257410003c0c60/$File/Sustainability%20review%202007.pdf) (August 2008)

End users of older automation systems essentially had to invest in two separate systems: a basic process control system and a separate safety instrumented system. Nowadays, suppliers differ in their opinions about the acceptability of implementing safety and basic process control functions in a single system with common processors. Some argue that integration reduces overall integrity, while safety, which faces ever-increasing regulation, is compromised.

The debate about integration is set to continue but one company that has been more constructive than vocal about this topic is ABB. As an established supplier of safety systems for hazardous processes since 1979, ABB launched the unique 800xA HI (High Integrity) combined safety and control architecture as part of the successful 800xA Extended Automation System. With this architecture, ABB has proven that true integration is possible, and functional separation of control and safety is ensured using modern high-integrity processing techniques, firewalls and active diagnostics. The system also is fully compliant with the requirements of the international functional safety standards.

Today's hardware and software technologies, in the hands of professionals operating under rigorous functional safety management procedures, can deliver new system architectures with higher levels of control and management functionality, and safety compliant integrity.

# Integrated but separate

Advances in integrated and safety control

Roger W. Prew

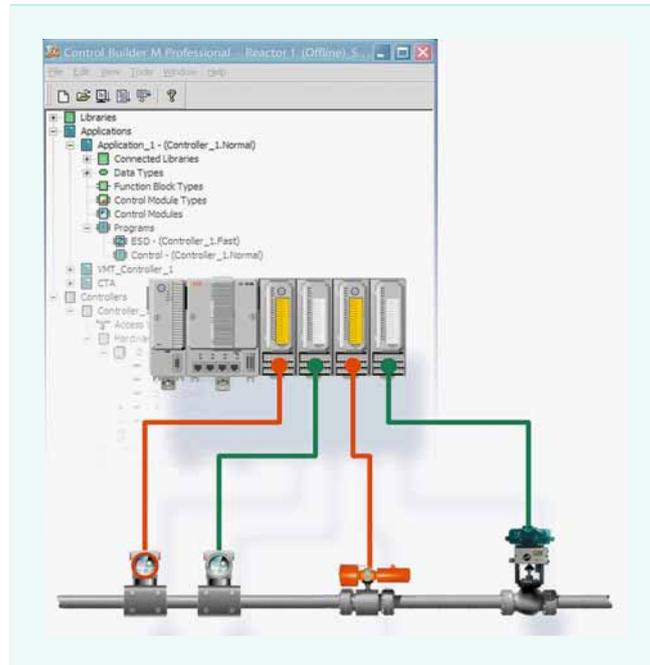


What are the advantages of integrating a safety instrumented system (SIS) and a basic process control system (BPCS)? For one thing, the lifetime cost of ownership of the system is significantly impacted, as are project design, engineering and modification costs. At the system definition phase, the flexibility of being able to transfer inputs and outputs (I/O) and functions between the SIS and the BPCS – without materially altering the system architecture – improves the efficiency of the design process and results in a more cost-effective solution. During system integration, this same flexibility ensures that the split between BPCS and safety matches the actual requirement and has not been forced into an architecture that was ordered many months earlier.

ABB's 800xA HI combined safety and control architecture has proven that true integration is possible, and functional separation of control and safety is ensured.

Cost savings arising from common configuration tools, communications networks, spare parts, maintenance, training, service and upgrades are obvious, but the biggest advantage is an increase in data access among the safety system, the distributed control system (DCS) application and process-management tools. Real-time connection of parameters between safety and DCS applications – only possible

1 ABB's System 800xA HI enables an increase in data access among the safety system, and the DCS application and process-management tools



if the two applications are executed in a single common controller node – means that expensive field equipment and wiring can be shared, thus optimizing the physical architecture 1.

Moreover, full integration means that all data associated with the safety instrumented function (SIF)<sup>1)</sup>, such as the safety integrity level (SIL) calculation, system and field-device diagnostics, trip frequencies, trip responses, valve condition and so on, are available to the BPCS asset management system. In addition, the high-level data collection and analysis tools of a BPCS can be exploited in a common and consistent way by the SIS 2.

#### Regulations and standards

Process safety has gained corporate importance especially since the catastrophic incidents that occurred at Flixborough<sup>2)</sup> (UK), Serveso<sup>3)</sup> (Italy),

Bhopal<sup>4)</sup> (India) and on board the Piper Alpha<sup>5)</sup> North Sea production platform. Now process safety expertise has extended into the general skill set of engineers and operators, and many industry-wide guidelines for process safety have been developed. The current industry standard for electronic and programmable systems, IEC 61508<sup>6)</sup>, is the result of concerted efforts by industry and regulators over the past 30 years. The global objective of such a standard is to ensure that proper risk reduction strategies are adopted by all industries with hazardous processes so that the incidents mentioned above can be prevented. This generic standard and the process industry's specific standard, IEC 61511<sup>7)</sup>, are essentially advisory. However, they

are now considered "good practice" by regulators in the United Kingdom and other industrial countries, and also as a means of determining whether a reasonable practical level of electrical, electronic and programmable electronic safety (E/E/PES) has been achieved. The standards are used to benchmark installations and are, for all intents and purposes, considered mandatory.

IEC 61511 defines methods of assessing risks associated with a particular hazardous process and it determines the risk reduction the safety system(s) must achieve. The standard is prescriptive in that risks must be assessed and reduced to "as low as is reasonably practicable." It does not however prescribe what technologies and architectures should be used to achieve the reduction.

#### Footnotes

<sup>1)</sup> A safety instrumented system (SIS) contains many safety loops or safety instrumented functions (SIFs), each with its own safety integrity level (SIL).

<sup>2)</sup> See <http://www.hse.gov.uk/comah/sragtech/caseliflixboroug74.htm> (Retrieved October 2, 2008)

<sup>3)</sup> See <http://www.chm.bris.ac.uk/motm/245t/245th/seveso.htm> (Retrieved October 2, 2008)

<sup>4)</sup> <http://www.bhopal.org/whathappened.html> (Retrieved October 2, 2008)

<sup>5)</sup> <http://www.answers.com/topic/piper-alpha> (Retrieved October 2, 2008)

<sup>6)</sup> IEC 61508 is the international standard for electrical, electronic and programmable electronic safety (E/E/PES) related systems. It sets out the requirements for ensuring that systems are designed, implemented, operated and maintained to provide the required SIL.

<sup>7)</sup> The IEC 61511 standard refines the functional safety requirements laid down by IEC 61508 specifically for the process-industry sector. It provides guidance in the proper application of a safety instrumented system (SIS).

## Productivity

### Current technologies

Many of the stand-alone safety systems currently available on the market pre-date the new IEC standards and employ a variety of technologies to achieve the high-integrity control required for safety applications. “High integrity” normally suggests a combination of fail-safe and fault-tolerant operation. Fail-safe ensures that if a fault occurs the system will react in a predetermined and safe way, whereas fault tolerance minimizes the likelihood of a failure that would prevent the system from performing its functions. These two terms often get confused! A fault-tolerant system may not be fail-safe. Just because it may be redundant or triple-modular redundant doesn’t automatically make it suitable for safety applications. Also, a fail-safe safety system does not require redundancy to achieve its SIL. Redundancy is built in solely to improve system reliability and availability.

The 800xA HI safety system shares a common processing unit and other components with the DCS, and brings a number of significant enhancements to the overall BPCS package.

The 1oo2 dual, 2oo3 triple and 2oo4 quad systems available on the market today come from a design era that

used redundancy and fault tolerance as a means of reducing the probability of a dangerous failure occurring. Today, dangerous failure modes can be completely eliminated and 100 per cent diagnostic cover can be provided to protect integrity without resorting to duplication. The requirements of “fail-safe” for “safety integrity” and “fault tolerance” for “availability” can now be considered independently and used when and where they are applicable [6](#).

There is always much debate about the hardware reliability of electronic and programmable systems. However, modern surface mounted, high-integration electronics is considered extraordinarily reliable. In an SIS, the logic solver hardware is the most reliable element in the entire safety loop! More evidence can be found in some modern simplex systems where the mean time between failure (MTBF) figures are better than the last generation dual or triple systems. In fact, the triple and quad systems suffer from the law of diminishing returns on reliability in that the inherent failure rate rises in proportion to the increase in components and complexity.

### A new generation of system

The new-generation 800xA Extended Automation System from ABB is flexible enough to either combine the control and safety functions within the same controller or keep the functions separate but within the same integrated network. Known as the 800xA

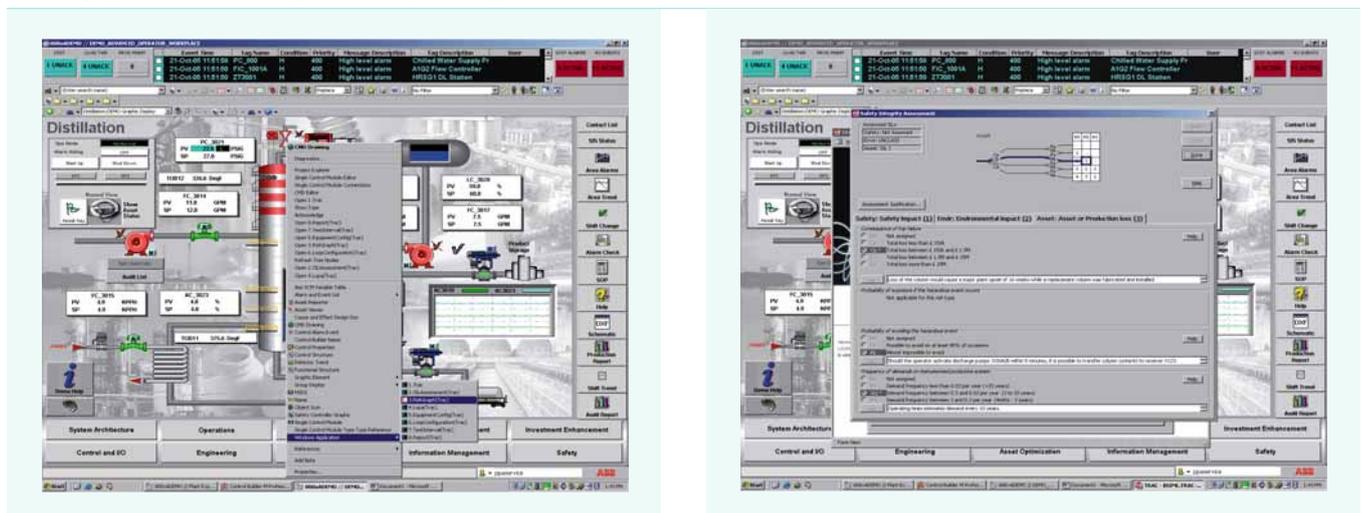
High Integrity (HI), it is definitely not a “modified DCS” or a DCS with added safety functionality. Instead it is a system designed from the outset to meet the requirements of the safety market and the current safety standards.

Safety-related programs are compiled using a limited instruction-set compiler certified for 800xA HI safety programs.

Many people erroneously believe that as long as the calculated probability of failure on demand (PFD) is within the right band, the system complies. There are four key requirements that must be met for a safety-related system to meet the aforementioned standards:

- Reliability (PFD) is of course important and the figures for all subsystems that make up the safety function must form part of the certified data set so that the overall loop SIL can be assessed.
- The safe failure fraction (SFF), which is a measure of the ability of the system to detect and avoid dangerous failure modes, is also part of the certified data set.
- Any constraints or integrity advantage resulting from the complete system architecture must be assessed and the implications on the SIL rating documented.

**2** Risk graph for a related safety function to protect against a hazardous event



■ Finally, the systematic integrity of the system including the development processes utilized, the life-cycle safety management of the system, and the methods used to develop and prove high-integrity software must also comply with the letter of the standard.

A fault-tolerant system may not be fail-safe. Just because it may be redundant or triple-modular redundant doesn't automatically make it suitable for safety applications.

The development of the 800xA HI safety system addressed the above issues. The design teams operated under audited functional safety management processes and the design concept and detail was approved at every stage by TÜV (the TÜV Product Service is considered to be the foremost independent certification authority in the business) <sup>4</sup>. A certification specialist on the team, helped by third-party consultants, steered the detail design continuously, confirming compliance with the requirements and the standards.

The 800xA HI safety system shares a common processing unit and other components with the DCS, and brings a number of significant enhancements to the overall BPCS package including:

- Higher BPCS reliability through:
  - Diagnostics – extensive diagnostic cover is a prerequisite for integrity.
  - Determinism – the safety model brings with it a deterministic execution model.
  - Integrity – this brings greater reliability and accuracy of measured values and control action.
- Faster communication between BPCS and SIS functions allows a higher degree of process-control optimization with respect to the actual safety boundaries (or safety distances).

**Integrated but separate**

The debate about the separation of the safety function from the BPCS will no doubt continue. However, the IEC 61508 and IEC 61511 standards do actually recognize that safety and non-safety functions can reside in the same system if “it can be shown that the implementation of the safety and non-safety functions is sufficiently independent (ie, that the failure of a non-safety-related function does not cause a dangerous failure of the safety-related functions)” (IEC 61508-2 clause 7.4.2.3). The standards also require that the possibility of common mode-dependent failures is reduced to an acceptable level (IEC 61511 Part 1 clause 9.5.1/2).

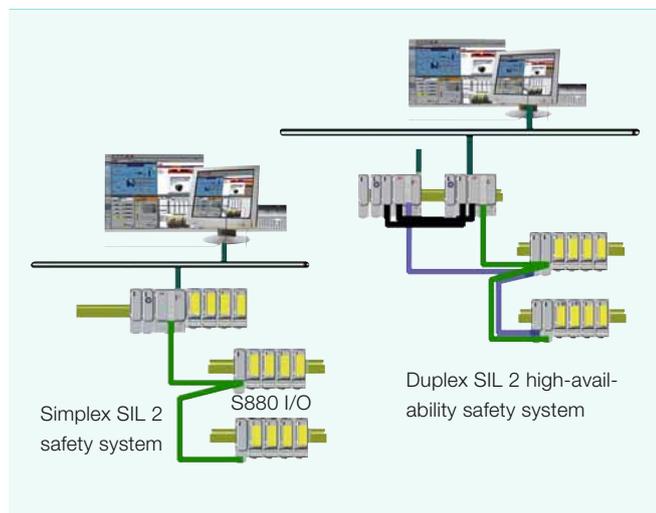
ABB's new-generation System 800xA is faithful to these requirements. The modular nature of the new system meets the standard requirements for functional separation and common mode failures. Memory partitioning,

separate execution contexts, firewalls and stack management techniques that come from the defense and high-integrity data-processing worlds ensure that safety and non-safety programs running in the same processing environment are actually separate and non-interfering. The integrity of the safety function is assured by limiting general communication with the man-machine interface (MMI) to read-only, and instituting a “safe write” function for overrides that can only be enabled by manual intervention at the controller. Peer-to-peer communications between safety and non-safety functions is strictly controlled to ensure integrity of the safety function. Additional cyclic redundancy checking (CRC) and relevance checking means the peer-to-peer network can be considered a gray channel.

The 800xA HI is a system designed from the outset to meet the requirements of the safety market and the current safety standards.

Detailed analysis was carried out against the layers of protection analysis (LOPA)<sup>8</sup> method of risk reduction. This analysis confirmed that the LOPA credits for protection functions, which are implemented in the DCS application and operate in either a combined control and safety node or a separate

<sup>3</sup> System 800xA HI safety-system architecture



<sup>4</sup> ABB's 800xA HI safety system is certified to the IEC 61508 and IEC 61511 safety standards, and approved by TÜV.



## Productivity

800xA node, are equivalent to those implemented in systems with totally different control and safety systems 5. The additional integrity gained from running BPCS applications in the 800xA HI controller outweighs the additional risks from possible common mode failures.

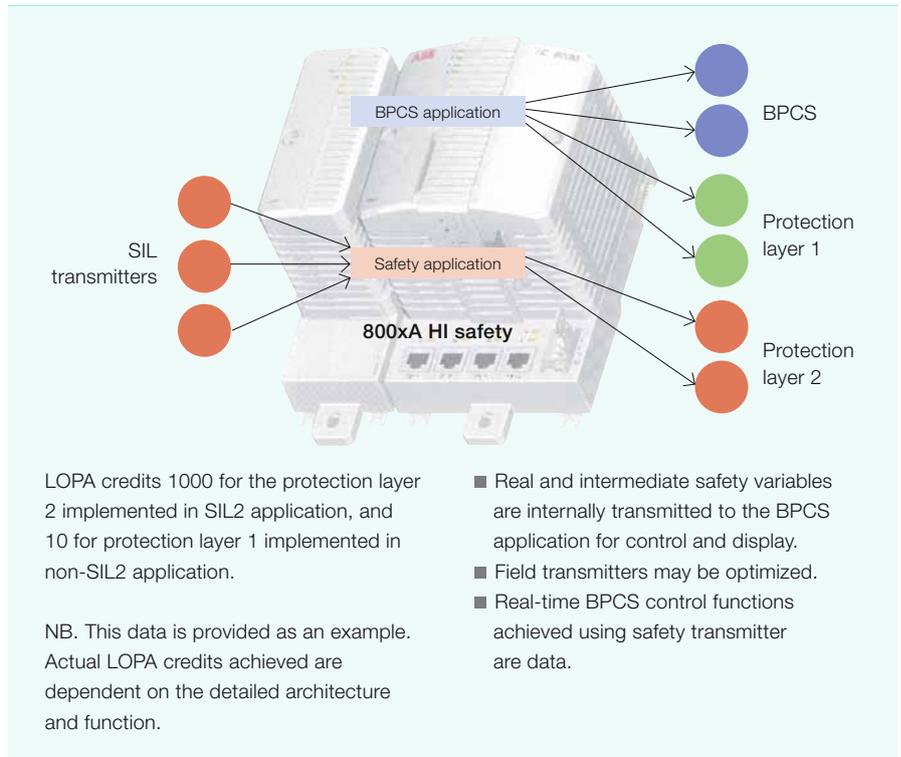
To the oil & gas markets, System 800xA HI offers a redundant architecture that can be independently implemented at the I/O level and at the operator level to add fault tolerance.

Safety-related programs are compiled using a limited instruction-set compiler certified for 800xA HI safety programs. During the compiling process, additional compiler test suites and CRC ensure the integrity of the compiled safety program. The block execution of the application during run time is verified for order, timing and discrepancy. Internal communications between processing elements and I/O are duplicated and double checked using proven techniques to ensure that all erroneous or unexpected messages are ignored. The use of diverse and dissimilar hardware in the I/O and processors, and a TÜV-certified real-time operating system (RTOS) in the safety module ensure that the System 800xA HI meets the integrity requirements of IEC 61511 on all counts.

### Highest reliability and availability

The 800xA HI design is inherently fail-safe with near 100 percent diagnostic coverage even as a simplex application (ABB claims 99.9 percent SFF and there are actually no known dangerous undetected failure modes in the system). This is achieved by virtue of an initial hardware design intended to fully meet the requirements of SIL3 (Four SIL levels are possible, with SIL4 being the most dependable and SIL1 being the least<sup>9</sup>). Hardware diversity in the I/O, local CRC and shutdown control, together with the unique processor/safety module architecture, eliminates common mode

### 5 Functional separation



faults. In addition, audited failure mode and effects analysis (FMEA) and failure rates place the product within the top 6 percent of the SIL3 band. Audited PFD figures are published and based on a proof-test interval of eight years.

Audited FMEA and failure rates place ABB's 800xA HI SIS within the top 6 percent of the SIL3 band.

In the oil & gas markets, safety-logic solver systems are expected to (a) run without interruption for at least 15 years and (b) endure all sorts of upgrades, modifications and changes during that time. System 800xA HI offers a redundant architecture that can be independently implemented at the I/O, the processor and the operator-workplace levels to add fault tolerance – and hence high availability – to an already high-integrity system wherever it is required. This redundant system can also safely upgrade the system application online.

The debate about grassroots principles is set to continue, but history has

shown that progress is being made by challenging the accepted view – addressing the problem from a different direction whilst complying with the standards.

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### Footnotes

<sup>9</sup> LOPA is a simplified risk-assessment method for evaluating the risk of hazard scenarios and comparing it with risk tolerance criteria to decide if existing safeguards are adequate, and whether additional safeguards are needed. See Primattech Inc. (2005). FAQ sheet – layers of protection analysis (LOPA). Retrieved October 2, 2008, from [http://www.primattech.com/info/faq\\_layers\\_of\\_protection\\_analysis\\_\(lopa\).pdf](http://www.primattech.com/info/faq_layers_of_protection_analysis_(lopa).pdf)

<sup>9</sup> For a more comprehensive explanation of SIL, see "Safe instruments" on pages 96–99 of *ABB Review Special Report Automation Systems* (2007).



# Hand in hand

Integrating electrical and automation systems

Peter Tubaas, Martin Stannestro

As process plants get larger and more complex, automation systems must handle an ever-increasing number of signals. At the same time, the number of electrical consumers increases, making an electrical control system essential. The electrical control system is an automation system in itself, providing an interface between the process control and the electrical consumers and actuators. ABB takes responsibility for all these systems and their integration. By letting ABB handle the integration and all the interfaces, customers benefit from faster project execution, reduced re-engineering, higher quality and higher operational efficiency.

## Productivity

Electrical systems are clearly a core part of any process plant, providing electrical energy to drive motors, energize heaters and power lighting and auxiliary equipment. The electrical system is invariably complex, relying on thousands of components and kilometers of cabling. The complexity of the system increases with the size of the process plant. Such large process plants are reliant on automation systems to operate efficiently and safely. These automation systems will typically respond to tens of thousands of signals in a quick, predictable and reliable manner. The seamless integration of the electrical and automation systems are highly desirable in a process plant, a benefit recognized by ABB at the StatoilHydro Snøhvit liquefied natural gas (LNG) plant. Here, the electrical control and supervision System (ECSS) communicates with a wide range of equipment and ensures a stable power supply to the LNG facility.

No system is more critical to the processing plant than the combined safety and automation system.

#### Snøhvit

The Snøhvit field – named after the fairytale character Snow White – was discovered more than 25 years ago. The road to develop this gas field was long and winding, but the project finally went online in October 2007.

The uninhabited island of Melkøya, not far from the town of Hammerfest, has turned into the largest building site in Northern Europe, and the largest construction project that Norway has ever seen.

Gas from the Snøhvit field, approximately 140 kilometers offshore in the Barents Sea, is flowing into the gas processing plant for treatment and shipping to the global LNG market. The core products of the plant are liquefied natural gas (LNG; 5.67 billion m<sup>3</sup>/year), liquefied petroleum gas (LPG; up to 250,000 tonnes/year) and condensate (up to 900,000 m<sup>3</sup>/year). All products are exported by ship.

Snøhvit is the first development in the Barents Sea. The oil and gas fields were discovered in the early 1980s. Combined with the adjacent Albatross and Askeladd fields, Snøhvit contains more than 300 billion m<sup>3</sup> of natural gas. Gas is extracted from the seabed using subsea equipment, which is operated remotely from Melkøya. The subsea control system was delivered by ABB in the United Kingdom (now Vetco Aibel). The topside of the subsea control system, which is an integrated part of the overall Safety and Automation System (SAS), was delivered by ABB in Norway.

#### Complete control of the plant

Snøhvit is an extremely complex installation. The process is extensive, encompassing subsea control processing, complex LNG processes, and

storage and loading of the final products.

No system is more critical to the processing plant than the combined safety and automation system. The number of signals running through the Snøhvit process is enormous; the Process Control and Data Acquisition (PCDA) system has to handle more than 30,000 signals simultaneously. An unscheduled halt in production is extremely costly. Therefore, ABB's control systems are constructed and tested to provide the highest level of security and minimal downtime.

The hot exhaust gases from the gas turbines are used to provide heat for the parts of the process that demand high temperatures.

The philosophy of process plant owners in general, and StatoilHydro in particular, is to provide its operators with a “single window” into the plant. ABB's 800xA Extended Automation System provides this facility and was, therefore, chosen for the Snøhvit project.

#### Plant power demand

Complexes for liquefied natural gas require a reliable and stable energy supply. Most LNG plants are, however, situated in areas in which the

MS Nordlys, one of the ships of Hurtigruten – The Norwegian coastal ship operator – entering the port of Hammerfest



1 Snøhvit is located on the northern coast of Norway.



power supply is either unreliable or nonexistent. The Snøhvit plant is no exception and must, therefore, rely on its own power supply.

To meet the power demand, the Snøhvit plant contains a 1.65 TWh/year power plant with five gas-turbine-driven generators of about 50 MW each. These power the large refrigeration compressors of up to 65 MW, driven by variable-speed electrical motors, which are required to liquefy gases. The hot exhaust gases from the gas turbines are used to provide heat for other parts of the process. This setup saves energy and provides about 10 additional uptime days per year due to the much higher availability of electrical drivers (as compared to gas turbine drivers).

Snøhvit contains more than 300 billion m<sup>3</sup> of natural gas. Gas is extracted from the seabed using subsea equipment, which is operated remotely from Melkøya.

The Snøhvit plant not only includes its own power station and large compressor drivers, but also a large distribution network with several thousand relatively small electrical consumers. A large variety of ABB electrical components, products and systems are included in ABB's deliveries to the

plant. These include high-voltage switchgear of the EXK-0 type, rated for 145 kV, and medium-voltage switchgear of the UniGear ZS1 type, rated for 6.6 kV and 11 kV. Also included are optical arc detection systems to provide early detection and quick protective action of switchgear to extinguish arcs. Further, MNS-type switchgear is used at low-voltage levels of 400 V and 690 V. Some 500 cubicles supplying power to about 2,500 consumers are included at these voltage levels; of which some 600 consumers are INSUM starters (intelligent motor starters) and 75 consumers are ACS 800 variable-speed drives. ABB's protection and control unit (REF542) is used throughout the plant to provide the highest level of security and selective protection actions in the event of a fault in the power system.

#### Electrical control and supervision

The complex nature of the electrical system requires an automated ECSS. This system is required to unite the thousands of motors, switches, contactors and circuit breakers, and to minimize the effects should a fault develop. A single unscheduled shutdown for the entire plant is extremely expensive.

The ECSS is at the heart of the electrical system and communicates with the vast range of ABB products using serial links and Ethernet. It is also linked with the automation system and other third-party deliveries. The system consists of 48 AC800M controllers. The

ECSS processes some 44,000 signals at any one time – more than the plant's automation system. The ECSS provides a wide range of functions, enabling a stable power supply to the plant, lowering operation costs and reducing emissions, while at the same time increasing safety.

The uninhabited island of Melkøya, not far from the town of Hammerfest, has turned into the largest building site in Northern Europe, and the largest construction project that Norway has ever seen.

An important part of the ECSS is the Power Management System (PMS). Since a relatively small fault may lead to a cascade of equipment shutdowns that could affect a large part of or the entire plant, faults must be handled quickly and appropriately to avoid a domino effect. ABB's PMS is also based on the 800xA Extended Automation System and is designed to monitor, control and protect all sections of a process plant. It includes functions such as:

- Supervisory control and data acquisition (SCADA), including generator, circuit breaker, mode and motor control
- Power control, including tie-line control, peak shaving and load sharing

An ABB engineer taking an overview of the plant at Melkøya (Photo: Peter Tubaas, ABB)



Two ABB engineers discussing the plans for the day at the LNG plant in Melkøya (Photo: Peter Tubaas, ABB)



## Productivity



- Load shedding, including fast, slow and frequency-based load shedding, as well as manual load shedding

Probably one of the most important and most frequently relied upon parts of the PMS is the load-shedding function, which helps ensure that the consequences of any one fault in the electrical system have the smallest possible impact on the functioning of the plant. ABB has delivered and commissioned more than 30 PMSs worldwide, demonstrating that the PMS substantially improves plant uptime, efficiency and reliability.

**ABB can draw on more than 50 years of experience with automation and electrical systems to optimize their integration.**

The ECSS not only provides an interface between the process plant's automation and electrical systems; it also provides indispensable functionality and reliability in a plant where a system shutdown could cost millions of dollars. Although full communication and data exchange with the process plant's automation system is provided, the ECSS does not depend on it to operate. On the contrary, the ECSS can operate in isolation to ensure safe and reliable operation of the electrical system.

#### Main electrical vendor approach

In the past, oil companies and engineering, procurement and construction (EPC) contractors have very often purchased different types of equipment (eg, transformers, high-voltage switchgear, medium-voltage switchgear and low-voltage switchgear) under separate contracts. Project risks can be reduced, however, by including most of the electrical equipment and systems – as well as engineering – under one large contract. The result is lower costs and faster project execution with safer systems that are fully integrated and interoperable. Safety is improved during installation and commissioning since project coordination is more easily achieved with only one contractor.

StatoilHydro recognized the merit of such an approach and merged all purchases of high-voltage, medium-voltage and low-voltage switchgear, as well as the ECSS, for the Snøhvit project into a single contract. In addition to equipment delivery, ABB provided a wide range of engineering services, including a long list of electric network studies. These are required to ensure safe operation and maximum efficiency of the plant.

Since the Snøhvit plant is physically connected to the northern Norwegian power grid, it soon became of interest to study the dynamic behavior of the entire plant – including the gas turbine generator sets – and its connection to

the grid. ABB has performed a dynamic stability study that was used to set and adjust the parameters of the power management system, as well as the dedicated generator control algorithms. This ensures not only stable operation of the process plant, but also ensures that the process plant contributes to the stability of the northern Norwegian power grid – as required by the grid operator.

**Complexes for liquefied natural gas require a reliable and stable energy supply. Most LNG plants are, however, situated in areas in which the power supply is either unreliable or nonexistent.**

#### ABB at the cutting edge

ABB can draw on more than 50 years of experience with automation and electrical systems to optimize their integration. Uniting the electrical and automation systems is becoming a necessary feature of large process plants. Operating such plants without an automated system is almost unthinkable, not only for safety reasons, but also for reasons of cost savings and increased efficiency. Customers such as StatoilHydro rely on experienced companies like ABB to ensure safe and reliable plant operations.

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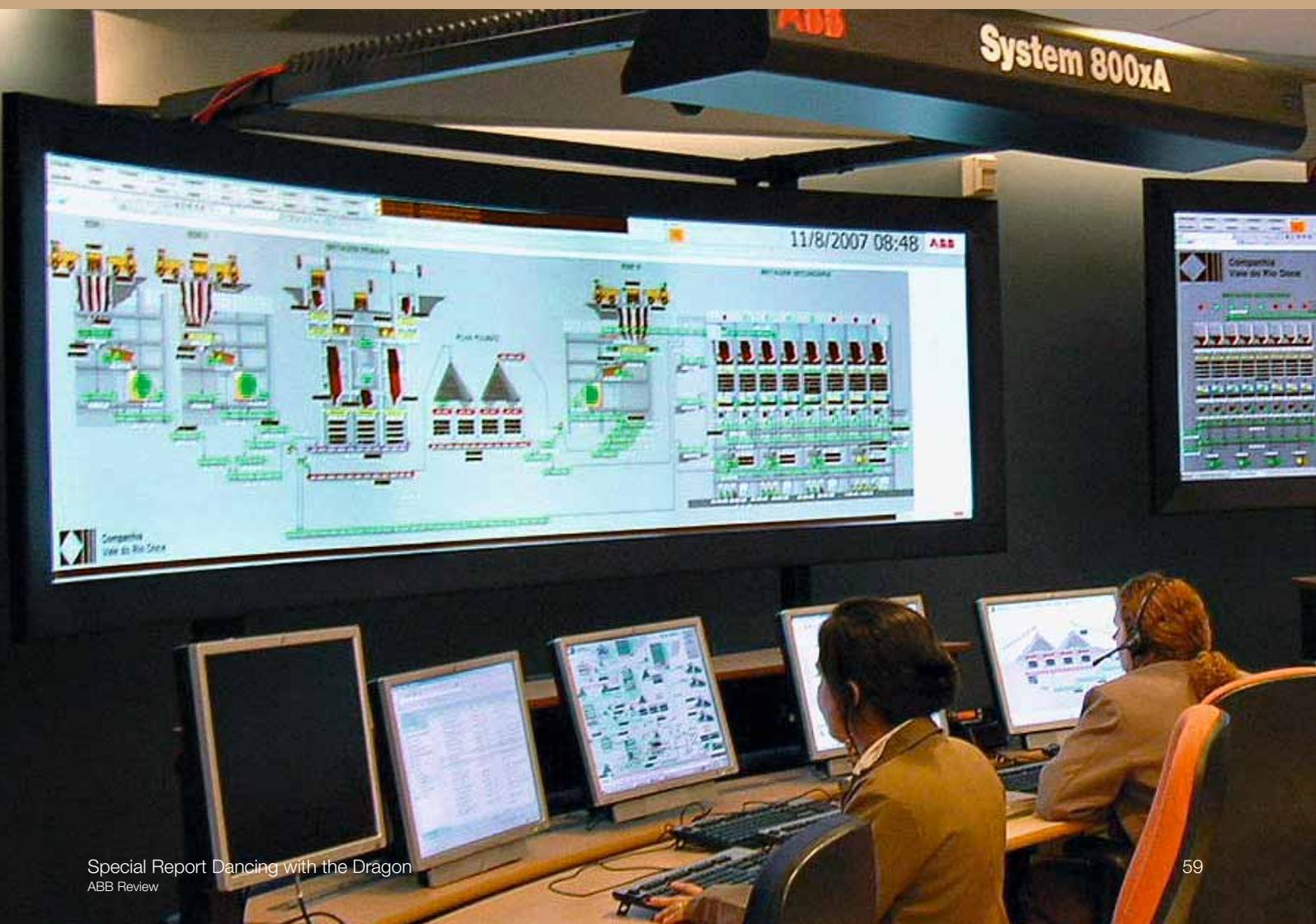
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# Projections of productivity

An operator's dream: ergonomics for the control room

Per Lundmark, William Zeng

It is a universal tenet that providing workers with the right tools augments their ability to produce efficiently. Progress in control room technology is a prime example of this. A good tool is defined not only by the scope of its functionality, but also by the ease with which it can be used. The operator needs rapid and intuitive access to relevant information at all times. A delay in obtaining information or a confusing format for its presentation increases the risk of misjudgment and lost production. ABB has taken on this challenge, taking control room ergonomics and interactivity to new heights, permitting operators to interact with all displays presented to them.



## Productivity

An improved overview of production, an increase in workplace efficiency and better ergonomics are principal features of ABB's complete workplace for control room operators, the System 800xA Extended Operator Workplace.

Operators can see the entire plant in an overall picture, as well as viewing several other selectable images at the same time. When a fault arises they can see it and respond more quickly.

This workplace builds on ABB's unique System 800xA software and continuing technical progress. It was developed in conjunction with two Scandinavian companies, and has been available on the market since 2006. Many successful installations are completed within several different types of applications. The experience shows a more effective, safe and profitable production result <sup>1</sup>.

One frequent comment from those customers that have seen and chosen the ABB System 800xA and the Extended Operator Workplace is that they would like the operators in the control room to have the best available production overview. "We want our operators to have a good overview of the production process and better possibilities to ensure we produce the highest level of quality for our very demanding customers. So we chose ABB's System 800xA Extended Operator Workplace for our control room."

Another comment is that the Extended Operator Workplace is effectively combining a large overview display with several regular monitors, all with full interaction. "The most important thing is that our operators can see the entire plant in an overall picture, as well as viewing several other selectable images at the same time. When a fault arises they can see it and respond more quickly. It is also easier to remedy. This enables us to minimize the number of halts in production."

This new presentation technology is changing the industry standard.

Process industries, petrochemical industries and combined power and heating plants are amongst those who have seen the advantages of having an efficient workplace for their operators.

More than 40 percent of all halts in production involve operator errors. In most cases, these can be traced to operators not being able to access vital information quickly enough.

At the core of the workplace lies ABB's 800xA automation system with its special sub-function, Operations. The operations package contains the operator interface and the software that can display information in different ways on screens of various types. It thus opens the possibility for overview pictures of a completely unique type.

With Operations, the foundation was laid for the development of a com-

<sup>1</sup> A more effective, safe and profitable production with System 800xA and the Extended Operator Workplace.



pletely new operator station. ABB inaugurated a working relationship with two Nordic companies, Creative Grafiska Möbler AB, a developer and producer of control room furniture, and 3D-Perception AS, a supplier of projectors for large-screen displays. After several years of development work, System 800xA Extended Operator Workplace has now entered many control rooms around the world.

The operator workplace incorporates an operator desk that is available in two sizes. The desk can be selected to contain one or two operator stations, each with up to four monitors, and one operator station controlling a large screen onto which two or three projectors mounted behind the desk beam information. The workstations can be configured as desired through the unique software in the 800xA system that controls the display of images in an ergonomically correct manner and totally automatically. Among other things, this enables numerous combinations of image displays between the monitors and the large screen.

ABB believes that ergonomics and overview are vital in enabling operators to be able to act quickly and avoid making mistakes. The goal is to minimize the number of unintentional production stops and to maintain a high, safe and consistent level of quality in production.

The development work followed a number of guidelines for a good control room workplace. It must provide a good overview of the process; be fully interactive for quick action; be modern and attractive; have equipment that replaces existing, difficult-to-manage wall panels; be able to integrate video monitors, such as CCTV; be designed in such a way that visitors do not disturb operators; be ergonomically designed with good lighting and a low level of noise; and permit consolidation and communication between different control rooms in the flow of production.

The most important thing in a new control room workplace is the option of displaying an overview. It is common in many control rooms in most

Operators are offered optimal support by interactive display technology from ABB



industries to have large screens that do not offer any means of interaction and often only display images of trends that are not of particularly great use. The operator in such a room struggles with perhaps only two monitors, incomplete information and ineffectively placed video monitors for the important camera monitoring.

More than 40 percent of all halts in production involve operator errors. In most cases, these can be traced to operators not being able to access vital information quickly enough.

**The operator workplace enables numerous combinations of image displays between the monitors and the large screen.**

The overview offered by System 800xA Extended Operator Workplace owes its advantage to the flexibly configurable display of information on different screens and projectors. Overview pictures can, for example, be displayed on the entire large screen, while the monitors show details, diagrams or other information. Or conversely, a single image, a diagram for example, can be spread across three

monitors as one total picture while the large screen shows trends in smaller windows. All images are opened correctly and automatically by the software in 800xA Operations, in separate windows and in a clear and readable format.

The large screen can be used in different ways:

- As a single continuous image
- In order to display all images in the system as overlapping images
- In order to build up group pictures of multiple images
- For displays for visitors
- For live video instead of separate video monitors

Another important purpose of the workplace is the improvement of the working environment for operators. ABB wishes to change the role of these operators so they can work more effectively and obtain greater satisfaction from the work they do.

The improvements to the working environment include the ability to raise and lower the curved working surface and the desk. Similarly, the large screen can be raised and lowered, as well as slightly bent in order to present a clear image from where the operators are sitting. By mounting the large screen directly at the rear of the desk instead of on a wall, as is usually the case, the overview is

## Productivity

- 2 The Matrox remote graphics unit helps reduce heat and noise emissions in the control room by providing only the user interface to the operators. The computers are located in a separate room.



not disturbed by passersby. An additional improvement to the working environment is the option of moving the computers entirely outside of the control room to deal with the prevalent issues of heat, noise, space and security.

An example of how this can be done leverages new technology developed by the electronics company, Matrox Graphics. Matrox introduces a trans-

mitter card on the workstation or server, which replaces the standard graphics card and can be fiber-optically cabled to a remote graphics unit on the operator side. The remote graphics unit contains all the necessary I/O including: four monitor ports, six USB ports for peripherals such as keyboard and mouse, and audio connections for speakers. Matrox remote graphics units work with all installations of System 800xA 2.



Working environments are a concern of the international consulting company ARC Advisory Group, which was commissioned to compare different operator workstation technologies and make recommendations for future developments. As part of its task, it studied the System 800xA Extended Operator Workplace and praised it, describing it as “an ergonomically optimized workstation designed to enhance the operator’s working environment and effectiveness with features that reduce fatigue and extend the operator’s range of understanding.”

ABB wishes to change the role of operators so they can work more effectively and obtain greater satisfaction from the work they do.

The feedback on ABB's operator workplace has been very positive. Following an installation completed in 2007, one customer remarked: “I take the greatest pride in working in the center of intelligence, where we find comfort, beauty, technology and security in every corner of the room. Working in an environment like this is certainly exciting and motivating for the whole team. Those responsible for this project deserve congratulations – it exceeded our expectations.”

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# Hard working but not exhausted

Reducing emissions from diesel engines

Ennio Codan



As more and more ships sail around the globe, China, in particular, is experiencing a huge increase in shipping traffic. Leading engine builders in China use ABB turbocharging solutions in marine, power and locomotive applications. With ever-tightening fuel efficiency and emissions requirements, China's shipbuilding and shipping industries look to ABB to strengthen their competitiveness.

Large engine development has always been closely connected with the development of the exhaust gas turbocharger. Every advance in compressor pressure ratio over the years has brought with it a new opportunity to improve engine performance by increasing the mean effective pressure.

At the same time, indications that a turbocharger generation is reaching its performance limits have also often been seen as a signal to investigate another possibility – multistage turbocharging.

### Two-stage turbocharging gets a boost

In spite of strong initial interest, very few of the early studies ever actually got as far as an industrial application. The 1990s saw this situation change. There were two main reasons: Firstly, engine development increasingly was being driven by emissions regulations – air pressure ratios were required that went beyond those needed just to increase the power output. Secondly, turbocharger technology had advanced so much that multistage turbocharging could now be given more serious thought. Recent years have seen the first commercial applications of two-stage turbocharging. However, these are restricted to automotive and high-speed industrial engines, which at the present time have to meet far stricter emissions requirements than the larger engines. Tougher emissions legislation for large engines is nonetheless now in force, and even more stringent regulations are in the pipeline.

### The efficiency conundrum

The usual approach when studying engine processes is to assume an ideal cycle and perfect air. However, the efficiency curves obtained in this way can be misleading. Under such ideal conditions we could expect to see thermal efficiencies of 68 to 70 percent being achieved with today's most advanced engines. Nevertheless, an

efficiency of 50 percent is considered to be very good. The difference suggests that there is considerable development potential. So why isn't the efficiency higher?

A look at the losses shows the main cause to be the gas properties (mainly because the specific heat varies with the temperature). Changing the engine's design has no effect at all on these. The heat losses are the second most important losses, but neither can these be reduced much by changing the engine's design. Both, however, are strongly dependent on the maximum cycle temperature.

ABB's studies show that the traditional "high temperature" approach to improving engine efficiency needs to be reconsidered. Also, high maximum cycle temperatures are known to promote  $\text{NO}_x$  formation in modern engines, and  $\text{NO}_x$  reduction is a key environmental target. How, then, can engine efficiency be increased without making the emissions worse?

### Miller timing

One way to do this is to reduce the temperature at the start of the engine cycle, for example with the help of Miller timing. In the Miller cycle, the combustion air is compressed to a much higher pressure than is needed to fill the cylinder for the desired air/fuel ratio. Closure of the inlet valve is timed so that just the right amount of air is sucked into the cylinders. The charge air thus expands, resulting in a lower temperature at the beginning of the cycle.

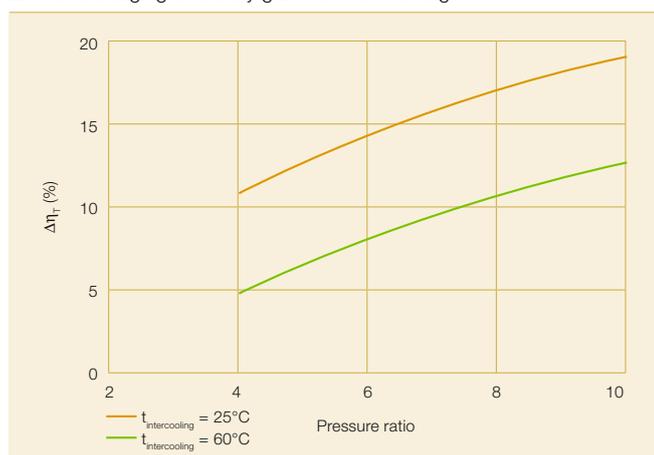
The remarkable improvement achieved with the Miller cycle is greater at low firing pressures. The required maximum pressure for 60 percent efficiency is about 80 bar lower with a Miller engine than for a conventional engine (190 versus 270 bar). Thus, with the Miller cycle very good efficiencies are possible at relatively low firing pressures.  $\text{NO}_x$  emissions are reduced at the same time thanks to the lower combustion temperature. It can be deduced from this that Miller timing allows, for the same efficiency, an increase in output without having to raise the maximum cylinder pressure, making it feasible to extend the design life span of a given four-stroke IC engine.

The potential benefits for gas engines are even greater. While these engines inherently produce less  $\text{NO}_x$ , the maximum cycle temperature tends to limit the mean effective pressure and efficiency because of the "knock" effect. Since the Miller cycle allows much lower combustion temperatures, the compression ratios, firing pressures and mean effective pressures could all be higher, considerably narrowing the output and efficiency gap between gas and diesel engines.

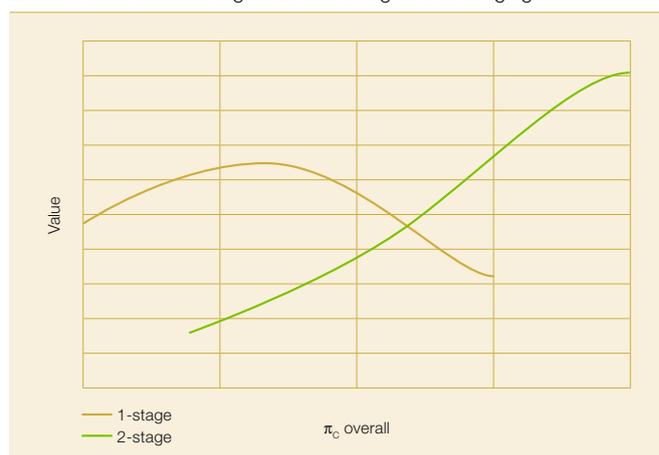
### Challenges for the engine designer

All of the above considerations are based on a theoretical Miller process. To achieve the mentioned results, however, the turbocharging system would have to deliver air pressures twice as high as those achieved today. Engine builders, too, would have to address certain issues. For example,

1 Turbocharging efficiency gain with intercooling



2 Trade-off between single- and two-stage turbocharging



## Productivity

the turbocharging system as a whole would have to be redesigned for much higher pressures and forces and the valve train system would need to be improved and controlled. It would also be necessary to look deeper into the issue of “cold” combustion and to develop new overall engine control strategies.



but the diagram will always look very similar. Because of this degree of uncertainty it would seem to be more reasonable to take one big step rather than lots of smaller ones, not least because of the repeated new investment – for both the turbo-charger manufacturer and engine builder – that these would entail.

### What about the turbocharging process?

In the idealized Miller cycle, the overall turbocharging efficiency is assumed to be 70 percent. This, however, would require a turbocharger efficiency of about 80 percent at a pressure ratio of between 8 and 10. A turbocharger able to deliver this does not exist, of course, and it is difficult to imagine that one will ever be produced commercially.

A two-stage system with intercooling would, however, allow figures close to these. The relationship between very high pressure ratios and high turbocharging efficiency is important here. Intercooling is key since, by allowing an approximation of isothermal compression, it improves the air compression process and consequently reduces the required compression energy. The efficiency gain depends on the intercooling temperature and on the overall pressure ratio **1**.

Intercooling, though, is not the only reason for the higher efficiency with two-stage turbocharging. Another can be found on the gas side: The expansion energy available for the two turbines is higher than with a single stage, because the losses in the high-pressure stage increase the energy at the low-stage inlet; also, the efficiencies of the compressor and turbine can be generally higher due to the lower specific loading. It is also expected that the bearing friction losses and the boundary layer losses will both be lower.

Another important point is that at higher pressure ratios smaller turbine areas are required even with higher turbocharging efficiencies. Starting with a moderate pressure ratio, the

effective turbine area increases with every power increase; this means that at part load the available pressure ratio decreases. Based on past experience, it could be presumed that high-pressure turbocharging will therefore result in even worse part-load behaviour. However, that is not the case. At least the boost pressure at part load will be higher than it is at present.

### From single-stage to two-stage

Although the switch from single- to two-stage high-pressure turbocharging is a major move, the argument for change and a considerable increase in pressure ratio is strengthened by the following considerations:

- Two relatively small turbochargers can be used since the turbine area is the controlling factor and decreases with an increasing pressure ratio.
- Intercooling results in a considerable increase in turbocharging efficiency; this benefit grows as the pressure ratio increases.
- System matching is generally not restricted by the map width and design conditions.
- Two-stage turbocharging offers good control flexibility.
- Reliability and durability are generally better because of the moderate pressure ratio at each step.
- Smaller turbochargers exhibit better acceleration and vibration behaviour.

The trade-off between single- and two-stage turbocharging can be simply deduced from qualitative value versus pressure ratio diagram in **2**.

The point at which the two systems are equal in value does of course depend on how the value is defined,

### High-pressure turbocharging's potential

Investigations carried out by ABB show that high-pressure turbocharging has wide-ranging potential for future engine development by enabling higher power densities, higher efficiencies and lower emissions. Used with the Miller cycle, for example, it promises a very favourable shift in the trade-off between efficiency and  $\text{NO}_x$  emissions. By keeping the air-to-fuel ratio at a satisfactory level, it could also allow better exploitation of exhaust gas recirculation's potential for  $\text{NO}_x$  reduction.

Based on the results of first tests with two-stage turbocharging on a real engine it can be said that a considerable amount of development is still necessary, both with regard to the turbocharging system and the engine. In view of this, it therefore seems reasonable to fully exploit the limits of single-stage turbocharging as the next development step towards lower emissions.

At the same time it can be said that major progress in high-pressure turbocharging, and especially two-stage turbocharging, could have very significant benefits – for the engine builder by providing more freedom to explore his engines' full design potential, for the end-user by reducing fuel consumption, and for the environment by lowering  $\text{NO}_x$  and  $\text{CO}_x$  emissions.

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# Concrete energy savings

Effective energy management in cement production

Matthias Bolliger, Eduardo Gallestey



The building boom in China is unprecedented, particularly in Beijing and Shanghai. With more families migrating to the cities, the need for new buildings continues to grow. With construction comes the demand for cement. To satisfy this demand, China has become the world's largest cement producer, generating roughly half the total global output. To produce cement, large quantities of thermal and electrical energy are required, typically accounting for about 30 percent of the production costs. The cement industry in China consumes about 6 percent of the nation's total energy and is mainly derived from the combustion of fossil fuels. The recent increases in fossil fuel prices have pushed cement production costs up. Since the industry contributes significantly to global CO<sub>2</sub> emissions, these costs are not only economic, but also environmental. ABB offers technologies that help increase cement-plant efficiency, maintaining productivity levels and cement quality, while reducing CO<sub>2</sub> emissions and fuel consumption.

## Productivity

The cement production process is complex, providing many opportunities for improvements to increase efficiency. ABB has a variety of products that can be installed to increase the fuel efficiency and the productivity of the cement manufacturing process **1**. During production, large fans draw air through the kiln, precalciner, mills and filters to an exhaust stack and smaller fans, in addition, push air into the grate cooler to reduce the temperature of the hot clinker leaving the kiln. All these airflows must be adjustable and controlled. Atmospheric conditions, process conditions and ventilation needs greatly affect the flow requirements. The method employed to control the airflow has a major effect on the running costs of the cement production plant. Controls can be retrofitted to manage the airflow. The least energy efficient method is to fit a damper with a fixed-speed motor, while the most energy efficient method is to fit a variable-speed drive (VSD) **2**.

Replacing dampers and fixed-speed motors, ABB's variable-speed drives offer a huge potential for energy savings, especially in the cooler.

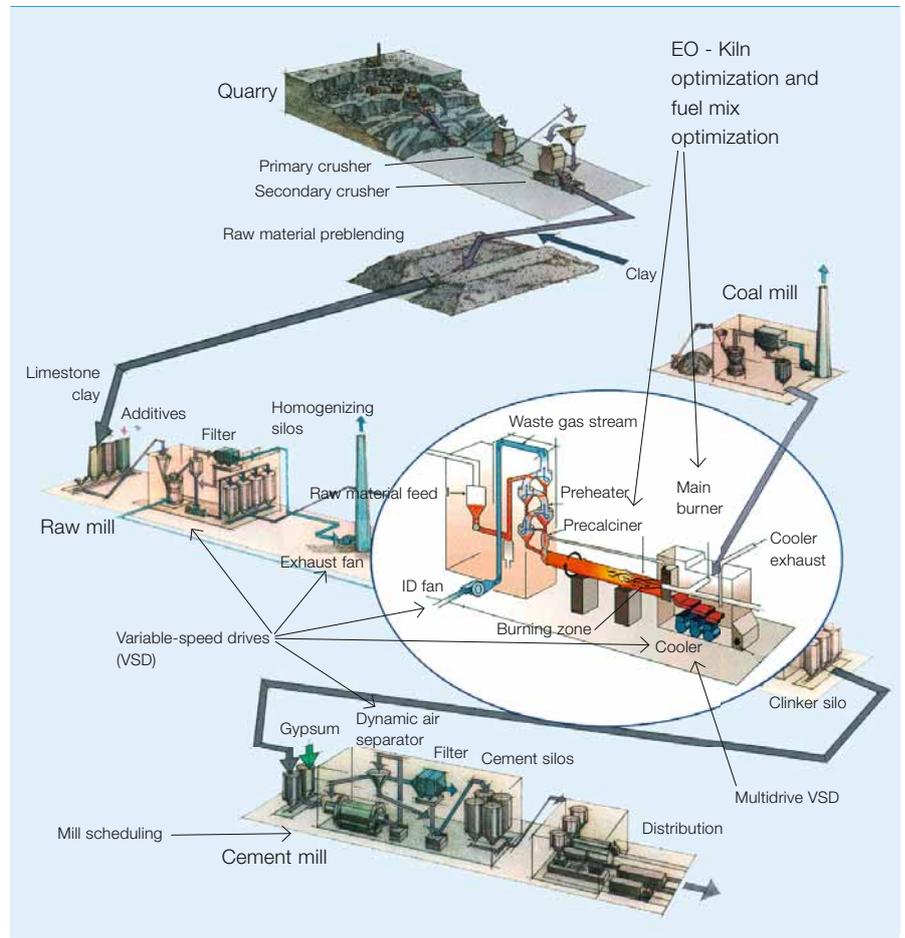
### Variable-speed drives save energy

ABB's VSDs can provide power savings of as much as 70 percent when compared with a damper and fixed-speed motor (depending on the required air-flow rate). During nominal production, large fans usually drive airflows at 90 percent, which even at this high flow rate means that a VSD can provide a potential power savings of 20 percent **2**. VSDs are usually installed in all-new plants today, but in older plants there is still big potential for energy savings by replacing dampers and fixed-speed motors with VSDs, especially in the cooler.

### Multidrive solution for grate coolers

The cooling of one ton of clinker requires approximately 10 percent of the overall electrical energy required to produce it. It therefore makes good sense to carefully consider the choice

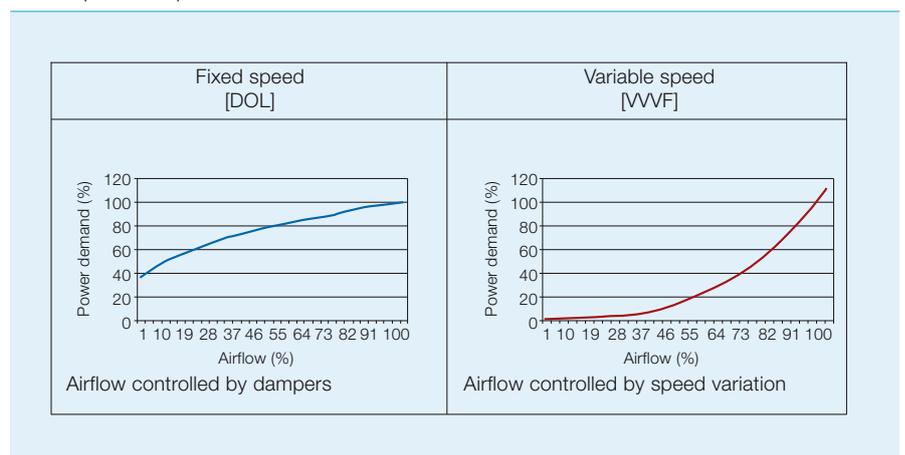
**1** Schematic of the cement production process showing how ABB products can be installed to increase fuel efficiency and productivity



of drive system used for the cooler. The ABB multidrive can be considered an optimized drive solution for the cooler **3**. It offers all the benefits of variable-speed drives, while retaining the desirable features of a single drive without the economic disadvantages. Unlike a single drive, which requires

its own rectifier, DC link and inverter, the multidrive system generates the required DC voltage in a central unit and feeds it into a common DC bus to which the single, independently operated inverters are connected. Since the individual inverters must not have the same power rating, a multidrive

**2** Comparison in power demand for an airflow controlled fan



package can consist of drives of very different sizes.

Some of the benefits include:

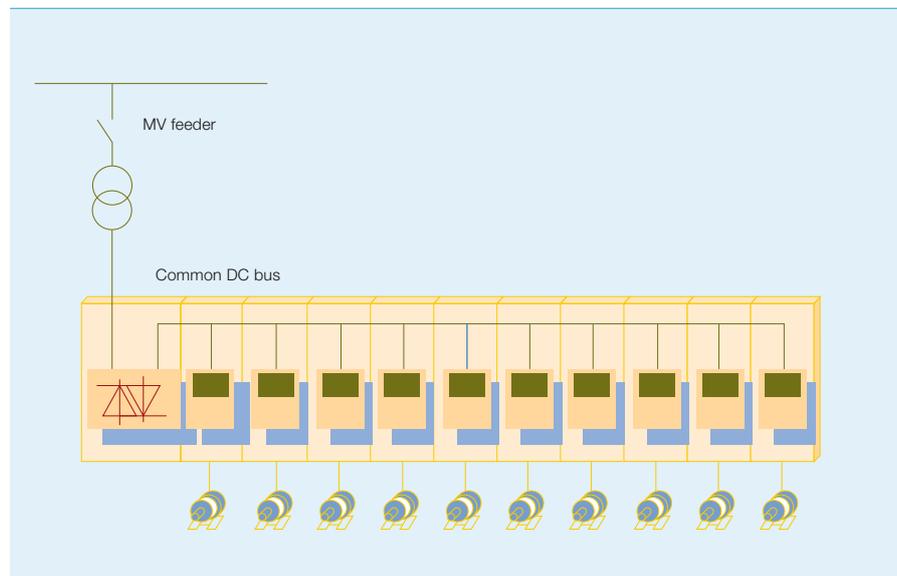
- Reduced cabling due to the single power entry for multiple drives
- Energy-saving motor-to-motor braking, which is required depending on the grate cooler type
- Reduced space requirement
- Elimination of the low-voltage distribution used for single drives or damper, and direct online motors in the case of a replacement
- Cost-effective reduction of harmonics using an active front-end supply unit or at least a 12-pulse line supply

The ABB multidrive can be considered an energy-saving, optimized drive solution for the cooler.

#### ABB Expert Optimizer saves energy

Cement manufacturing is a complex and energy-intensive process. A key stage in this process is the conversion of ground raw materials ( $\text{CaCO}_3$ , clay and/or shale) into clinker in the kiln. A typical operation uses kiln exhaust gases to preheat the raw materials before they enter the kiln. In the kiln's burning zone, the material is heated to about  $1,500^\circ\text{C}$ , where it partially melts and reacts to form clinker. Sub-

3 Basic configuration of a multidrive system layout with active front-end supply



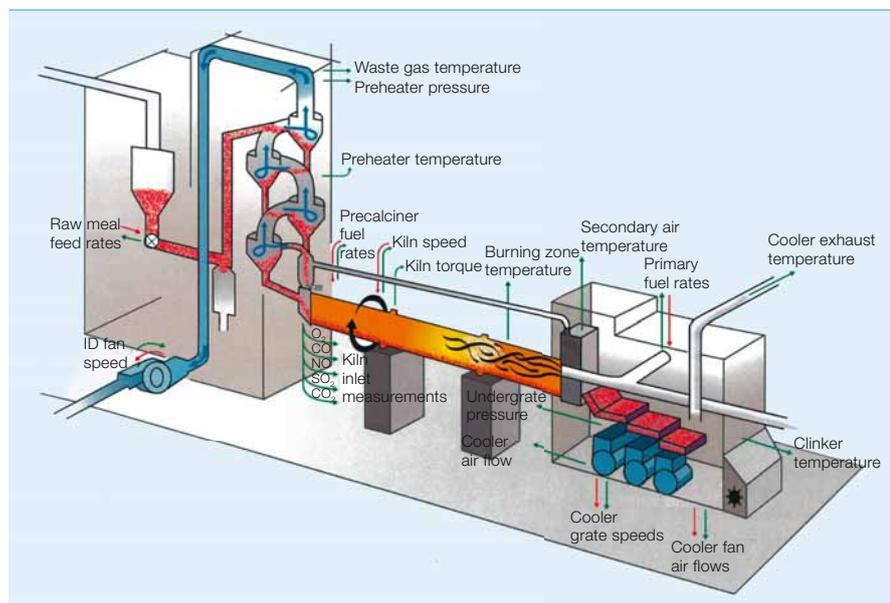
sequent processing continues to convert the clinker to cement, with the addition of small amounts of gypsum ( $\text{CaSO}_4$ ) and further grinding to produce a fine powder.

Conventionally, cement kilns are controlled by an experienced operator who constantly interprets the process conditions and makes frequent adjustments to control established standard set-points. This task is onerous enough, but is made even more difficult by the complex responses to these adjustments, time delays and the interactions between individual pro-

cess variables. These difficulties force the operator to take a conservative approach to kiln operation, using process temperatures that are higher than the optimal, leading to unnecessarily high energy usage.

The ABB Expert Optimizer (EO) system was developed upon the solid foundations of its highly successful and highly regarded predecessor, the ABB LINKman optimization system. The system improves on conventional control methods by constantly monitoring the various input- and output-signals from the kiln and responds by initiating appropriate actions 4.

4 Kiln schematic showing input and output signals of an EO system



The burning zone temperatures (BZTs) are crucial to product quality, as they affect the proportion of free lime (unreacted  $\text{CaO}$ ) in the finished product. Although this varies from one cement production plant to another, the basic principle is the same; namely, low BZTs will produce softer clinker with higher proportions of free lime content, and high BZTs will result in harder clinker with lower free lime levels 5. The higher the BZT, the higher the required clinker grinding capacity and therefore the greater the fuel consumption.

The BZT also affects the stability of the kiln's operation. A high BZT results in a more stable kiln, while a BZT that is too low can cause volatility, reducing productivity and even

## Productivity

causing stoppages. An unstable kiln operation causes major thermal stress on refractory brickwork in the kiln, thus shortening refractory brick life and causing premature expenditure. Unnecessary kiln downtime causes increases in the energy requirements per unit of clinker produced, ie, a higher energy-base loading (or higher minimum energy requirement). This is especially true when considering the additional energy required to restart the kiln.

Proper, stable kiln operation can reduce energy consumption and maintenance costs, increase kiln output and improve overall product quality. However, maintaining an optimum BZT at a minimum level while preserving stability is difficult to sustain for three reasons:

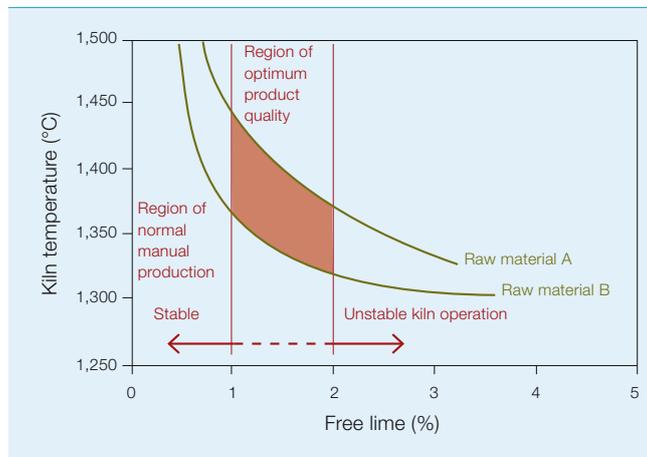
- Variations in raw material feed composition
- Complexity of kiln operation
- Long-time delays between kiln operational changes (ie, set-point changes and their effects)

The ABB Expert Optimizer system was developed upon the solid foundations of its highly successful and highly regarded predecessor, the ABB LINKman optimization system.

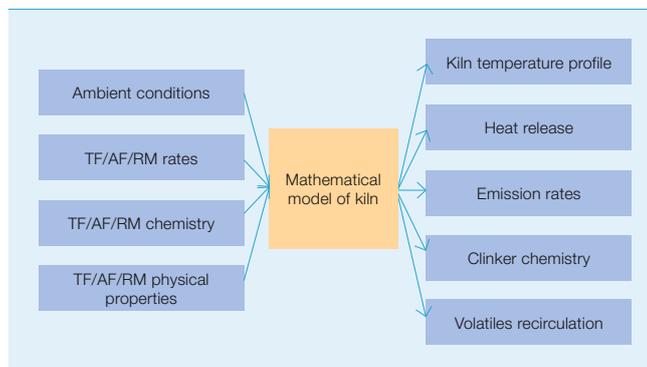
The EO advanced kiln control system, however, operates the kiln in an optimum manner, thereby ensuring a high-quality product, lower BZT and consequently, lower energy costs. The system achieves this by regularly making adjustments to the process every three to four minutes.

The EO is typically in control of kilns for more than 80 percent of its run time. Estimates based on measured free lime and nitrogen oxide (NO<sub>2</sub>)

5 Burning zone temperature in function of free lime



6 Kiln model inputs and outputs



levels made before and after EO installation suggest that fuel savings can, in some cases, approach 8 percent per kiln.

### Kiln fuel mix optimization

The EO comprises rule-based control with modern tools like neural networks, fuzzy control and model pre-

#### Factbox A delicate balance

The process and business constraints to be satisfied are numerous. Among the most important are:

- Heat balance
- Excess oxygen level
- Clinker chemistry
- Concentration of volatiles
- Emission limits (SO<sub>2</sub>, NO<sub>2</sub>, etc)
- Maximum, minimum and speed of change constraints on actuators
- Operative constraints on fuel consumption
- Separate consideration of combustion process in precalciner and kiln, contracts (with customers or suppliers) to be satisfied at any cost

dictive control (MPC)<sup>1)</sup>. Enhancements that offer optimal fuel management will allow efficient use of alternative fuels so that the kiln can be operated economically. The main idea is to use the data gathered by the information management systems (equipment, process, market and laboratory) to calculate the lowest fuel mix costs that satisfy the process and business constraints

#### Factbox

The basic element of this algorithm is a dedicated mathematical kiln model developed in EO, which is used for model predictive control. The optimization algorithms are able to cope with both hard and soft constraints, which enhance the robustness and reliability of the optimization process 6.

The implementation of this algorithm is such that the input data is updated at constant sampling times of about 15 to 30 minutes,

computations are executed and the new fuel set-points are passed to EO strategy for implementation. Between sampling times, the standard EO strategy guarantees process stability and optimal performance. In particular, this strategy enforces:

- Economically optimal reactions to changing conditions in fuel, waste and raw meal quality
- Strict satisfaction of environmental, contractual and technical constraints

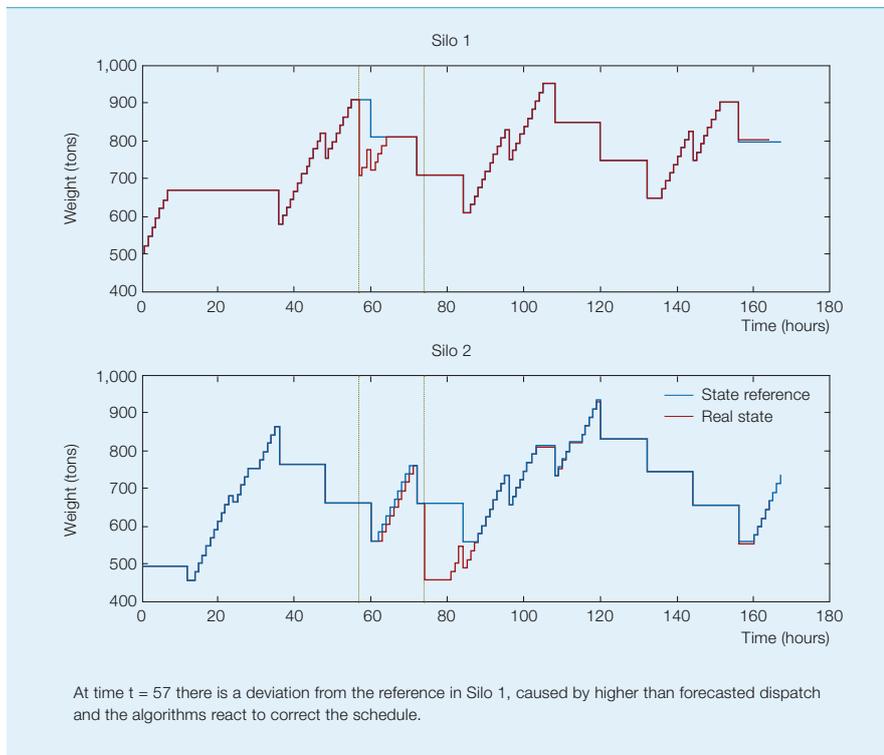
### Electrical energy management

Cement production operation runs 24 hours a day, seven days a week,

#### Footnote

<sup>1)</sup> Neural networks are a system of programs and datasets that attempt to imitate the way a human brain works. They draw on large datasets of earlier examples, thereby weighing up inputs and their significance. Fuzzy control is a term that describes how concepts (inputs) that are fuzzy – ie, not simply true or false, but with degrees of truth – can be analyzed. Model predictive control is an advanced method of process control attempting to predict the output of a process with respect to changing inputs.

- 7 An example of the rescheduling capability of the EO: The solid line shows pre-computed reference levels for Silo 1 and Silo 2, while the cross line represents the actual silo levels as measured by online sensors.



with very limited spare capacity or redundancies installed. Thus, most of the equipment has to run around the clock or during daylight hours (due to constraints such as quarry operating times). It is difficult, therefore, to find opportunities to reduce electrical energy usage. The main area of flexibility is confined to the cement grinding area.

ABB's EO uses the data gathered by the information management systems to calculate the lowest fuel mix costs that satisfy the process and the business constraints.

Currently, scheduling in the grinding area is performed manually, using heuristic rules and relying on operator experience. However, depending on the number of mills installed, cement grades produced and silos installed, manual scheduling, which takes account of various operating and contractual constraints, can be extremely

complex. Too often, the operator's choice is far from optimal. The following solution describes an optimized scheduling based on MPC technology.

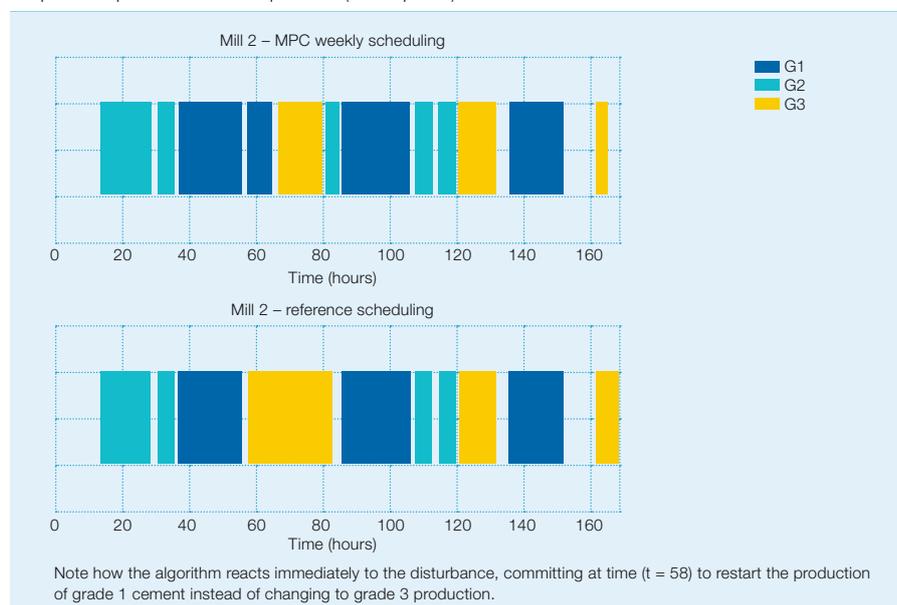
Using customer orders and energy price forecasts, the algorithm produc-

es a reference schedule for the whole grinding plant's operations; ie, what type of product each mill will produce and when 8. Here the functional units represent the costs associated with electricity consumption and the amount of low-grade cement produced (cement produced during the switch from one grade to another). Electricity cost reduction is achieved by scheduling production to periods when the electricity tariffs are lower, and ensuring that the contracted thresholds of maximum electrical power are not exceeded. Reductions of low-grade cement are obtained by minimizing the number of cement grade production changes.

By scheduling cement grinding to periods when electricity tariffs are lower, the costs of cement production can be reduced.

However, unplanned events such as component failures or unexpected product demands are frequent. MPC is able to react to such changes. In this phase, state variables are the silo levels, while the control variables are the commands to switch mills. The cost function is a weighted sum of

- 8 Algorithm response: The new control sequences (upper panel) are compared with the pre-computed control sequences (lower panel).



## Productivity



deviations from the values given by the MPC reference schedule. The typical sampling time is one hour.

ABB's EO can quickly react to differences between the predicted and actual levels of cement in the silos, rescheduling optimal production to meet demand.

In addition to physical constraints (silo capacity and mill availability), the grinding plant's operations must take account of time delays, which occur whenever a change of cement grade produced by a mill is made, so that the mill's throughput can be conveyed to a special silo. It must take account of changes in demand so that delivery time to customers is minimized. The optimization algorithm requires the sales forecasts for every type of cement grade. If the forecasted sales cannot be fulfilled, the algorithm will prioritize the cement grade produced. Furthermore, the optimization algorithm must evaluate the constraints on cement transport from the mills to the silos using, for example, available conveyor belts or bucket elevators. There may be three mills with only two independent transport routes. Multiple mills can simultaneously discharge the same cement grade using

the same transport route to a single silo; however, when different mills are producing different cement grades, independent transport routes must be used to fill different silos.

ABB's EO can quickly react to changes in the forecasted levels of cement contained by the silos **7**. Differences between the predicted silo levels and the actual silo levels, caused by higher dispatch, are detected by sensors in the silos. The algorithms react to correct the schedule and to reject the original ideal schedule. The algorithm immediately reschedules the mills to maximize efficiency, so that the supply of the correct grade cement continues to flow into the correct silo. A discrepancy between the forecast levels of cement in the silos and the actual levels has initiated the rescheduling of cement production by the mills, so that the planned change from grade 1 cement production to grade 3 cement production is postponed, optimizing the use of the mill **8**.

#### More efficient and cost effective

Energy management can help reduce thermal and electrical energy demands and can be used to source less expensive energy. Today, proven technical solutions and reliable equipment are available to ensure successful energy use without jeopardizing the quality and productivity of a plant. These solutions provide positive effects on the environment, and since energy prices have been escalating recently,

the returns on such investments can be made within increasingly reasonable time periods.

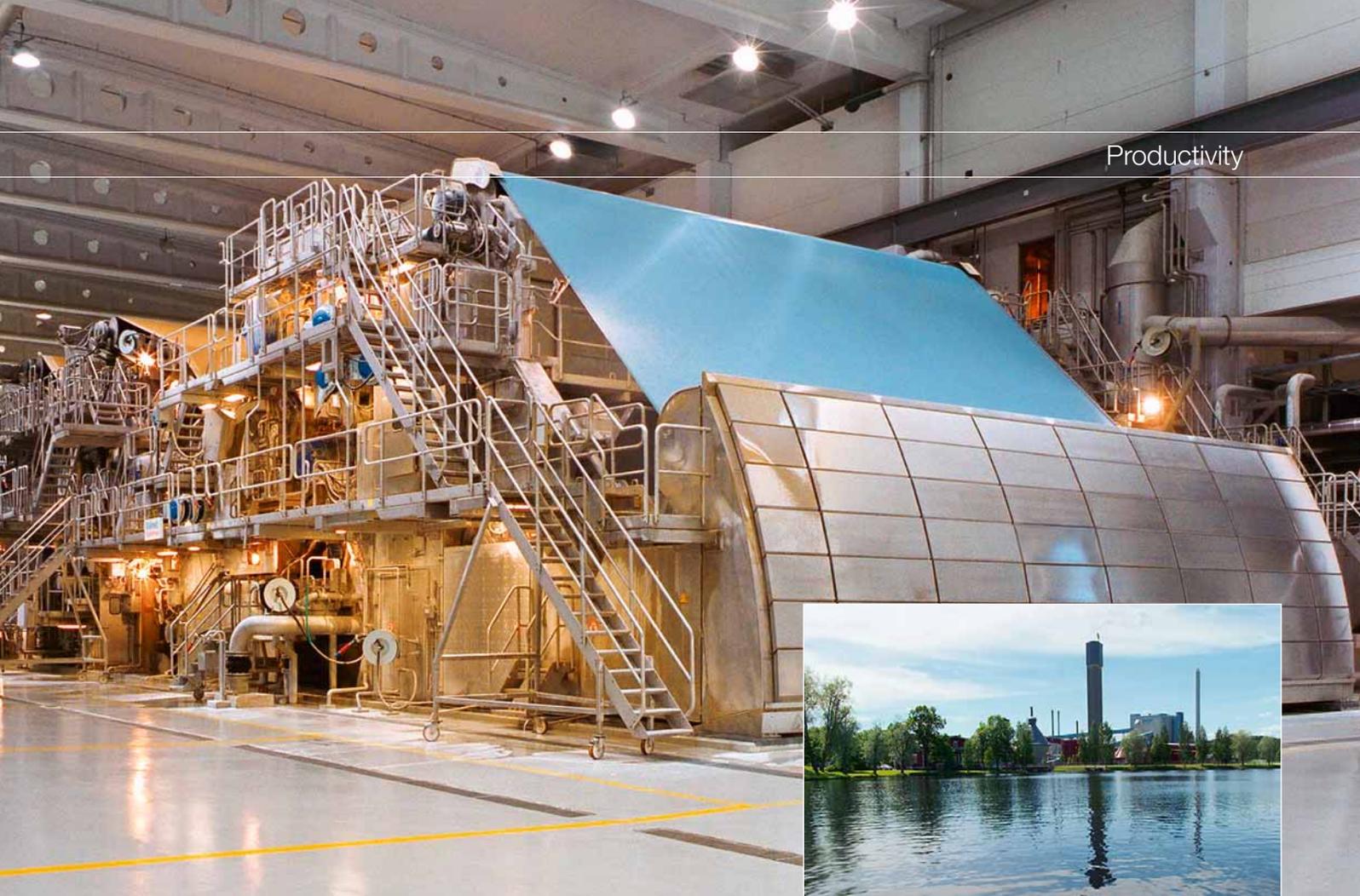
ABB's experience in the cement industry together with its board portfolio of products can help China reduce CO<sub>2</sub> emissions and increase energy efficiency.

ABB's experience in the cement industry together with its board portfolio of products can help China reduce emissions and increase energy efficiency so that the cement needed to build new offices and homes in the cities of China need not be such a drain on resources.

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# Networking

UPM centralizes its energy optimization and emissions trading within Europe with the help of ABB's Energy Management System

Jaakko Juntila, Marja-Liisa Parkkinen

UPM-Kymmene Corporation is one of the world's leading manufacturers of printing paper. Energy plays an important role in production and, as part of its corporate strategy, the company aims for a high level of self-sufficiency in energy production. Knowing the expected energy demand and optimizing the energy resources brings about significant savings.

To reach this goal, the company has, over the years, invested considerably in energy efficiency, availability, and in the predictability of energy use and supply. One of the key tools in this area is energy management. Energy Management Systems supplied by ABB have been in use at the Finnish mills for some time, and it was decided that to better manage and optimize energy in the whole corporation, it was best if all the European mills were linked together into the same system.

Thus, by early 2006, energy management systems had been implemented and are now running at all UPM production facilities in Central Europe. Similar systems already in use at Finnish mills have been upgraded to the latest version of the product.

Productivity

UPM-Kymmene has 10 paper mills in Central Europe and eight in Finland. Production is based on strong vertical integration as well as tight coordination of raw materials, energy and the production process. In fact, with the aid of several generations of energy management systems from ABB supplied over the past 20 years, UPM has been a leader in predicting energy needs. “Taking care of our energy balance, the focus of the ABB system, involves balancing our time-dependent energy consumption in real time with respect to surpluses or deficits,” said Anja Silvennoinen, Vice President, Energy at UPM. “In addition to energy generated by its own units, UPM-Kymmene purchases and sells energy to and from external partners and market operators.”

In 2007, the company was able to meet approximately 70 percent of its own electricity needs. In Finland, UPM is self-sufficient in electrical power, but outside Finland most electricity used by company mills must be purchased locally. The effective use of energy reserves and hydro-power contributed to an increase in profits for the energy division.

UPM’s centralized energy management system has been expanded to include UPM mills in Austria, Germany, the United Kingdom and France. From the beginning of 2005, all energy management information from these mills is consolidated in a control center system in Augsburg, Germany to yield

their total energy-balance history and consumption forecast. Because UPM-Kymmene trades energy with external partners, the center is able to balance the load and share resources across the entire network.

UPM’s centralized energy management system has been expanded to include UPM mills in Austria, Germany, the United Kingdom and France.

This consolidated information is routed from Augsburg to Jämsänkoski, UPM-Kymmene’s Finnish energy management control center, which optimizes the use of energy resources and electricity trading for the Finnish mills and controls the hydropower generation. As this older system in Jämsänkoski has been upgraded to ABB’s new product platform, UPM-Kymmene can get an overview of its entire European energy operations from a single place.

Predicting energy needs

Prediction lies at the heart of the integrated energy management system. Energy consumption is dependent on the operating mode of the mill – how the paper machines and other units will be run. Once the operating schedule of the units is known, their energy needs can be forecasted based on previous history. This information

can then be used to make real-time decisions on how to use, generate, purchase or sell energy. The decision making is supported by a model that takes into account the available resources, their prices and various operational constraints. A group of several mills can benefit from economies of scale to purchase and sell energy in the most effective way.

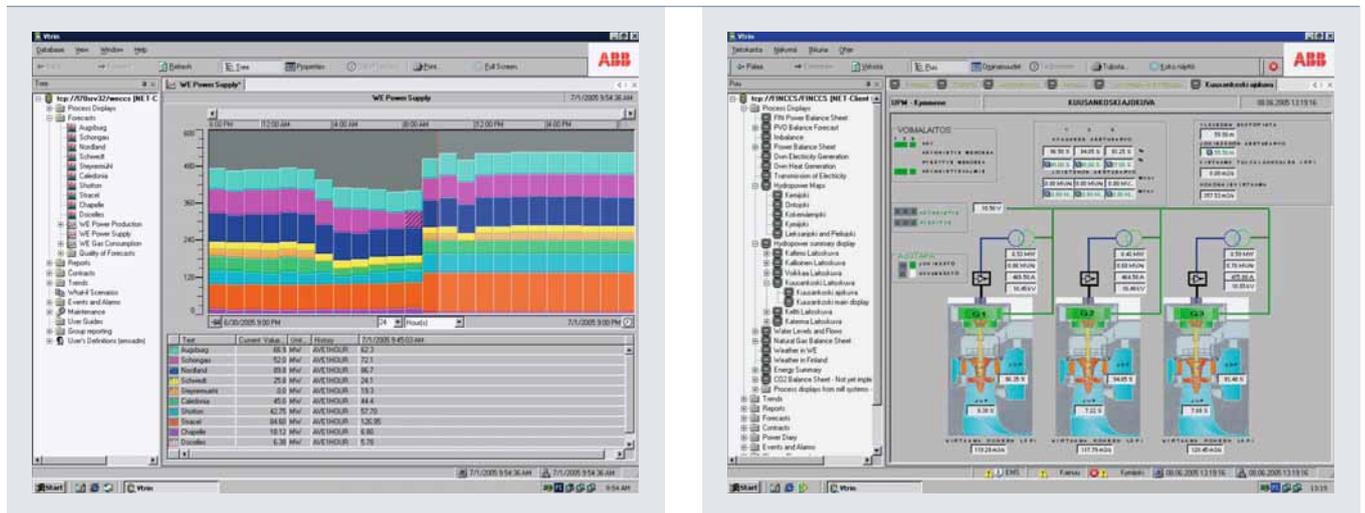
An essential step in the process involves feeding data – historical, real-time and forecasted – into one central

**Factbox** Real-time database (RTDB) and standard user interface (VTRIN)

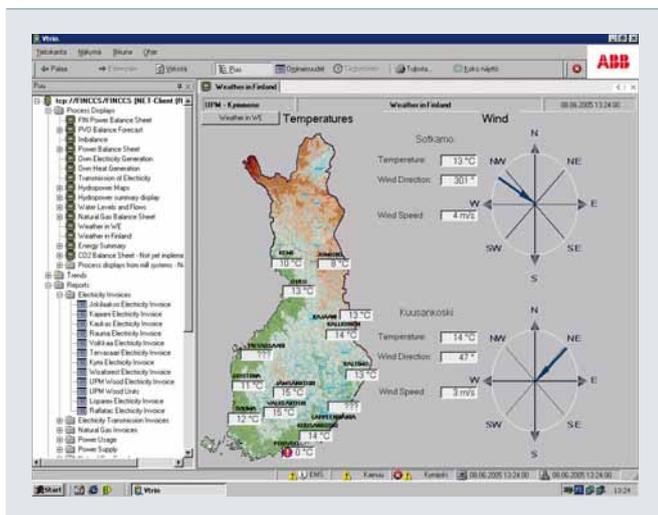
The database is implemented through ABB’s RTDB product, a relational database designed and optimized for process information management and extensive history recording. RTDB combines the benefits of an easy-to-use relational database with high reliability, performance and real-time functionality. Real-time process data is collected from various data acquisition systems through interfaces and is stored in the database.

The information in the database is available for all users through ABB’s standard user interface (VTRIN), which allows the flexible navigation, presentation and linking of process information according to the user’s preferences. VTRIN is based on Microsoft’s .NET architecture – modern development tools and architecture based on the latest trends in usability technology.

1 Historical, real-time and forecasted data gives the operator vital production and energy information necessary for decision making.



- 2 Weather data is necessary and available because of its effect on energy consumption.



database **Factbox**. This data allows the operator to see what has been happening in production, how much energy has been used and the amount required in the future.

An essential step in the process involves feeding data – historical, real-time and forecasted – into one central database.

#### Energy management and optimization

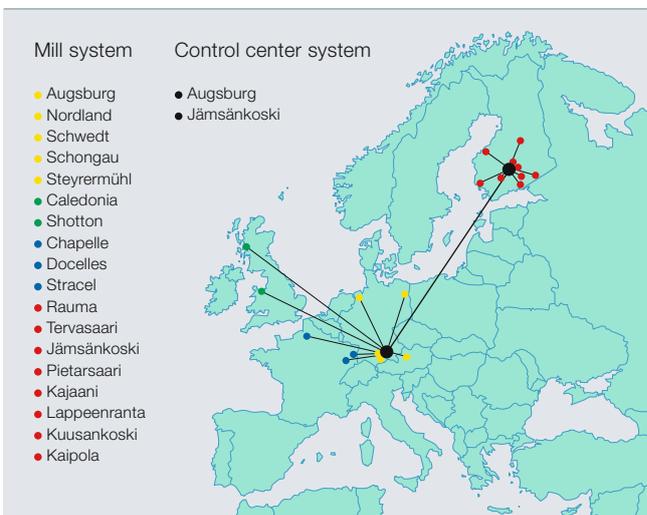
ABB has extensive experience in developing and supplying energy management solutions for the process industries and in particular for the paper and metal industries, which are very energy intensive. The company's energy management systems are built on the real-time database (RTDB) and standard user-interface platform (VTRIN) using a set of generic functional modules that are configured and parameterized for the customer's application. Such functional modules are available for energy consumption forecasting, energy contract and balance management (including sales and purchase recording, resource booking, and energy cost allocation to consumers), optimization, and real-time monitoring of energy balance and purchased energy 1 2.

Consumption forecasts for paper machines are derived from the planned production grade and rate, which may be entered into the system from the production planning system through an interface. Mechanical pulp production is a big energy consumer, and its energy consumption is dependent on the running state of the refiner and grinder units. Some consumers follow weekly load profiles, which can be used in their consumption forecasting. The total mill consumption is obtained by summing individual unit consumptions.

Energy Contract Management selects the energy resources to match the time-varying energy consumption at optimal cost. In addition, it also provides a number of related functions for system users. The total energy network is modeled as a number of balance areas, such that total consumption matches total production at all times. The balance equation takes into account a mill's generation, purchase and sales contracts in the balance area and any transfer of energy between the areas. The time resolution depends on the balance area, eg, it is one hour in Finland and 15 minutes in Germany, due to country specific regulations.

The system administrator can specify and set: the parameters for the various balance areas; energy trading partners;

- 3 UPM-Kymmene's corporate-wide Energy Management System includes mill-wide systems at 10 paper mills in Central Europe and eight mills in Finland, plus two inter-connected control center systems.



contract types; and the users' record sales and purchase transactions with prices, amounts, validity times and all other relevant information.

The results of the energy supply calculations together with measured energy consumption can be used to internally allocate energy costs, and bill consumers. They can also be used to verify external energy invoices.

The control center system compares the consumption forecast with available energy production capacity and existing purchase and sales contracts.

With the scenario management facility, the user can simulate "what-if" scenarios by modifying energy system parameters without affecting the real system data. For example, new purchase or sales contracts can be simulated to assess their profitability, or unit operating schedules can be changed to see how they affect related energy costs.

#### Eighteen mills in one energy net

The Finnish mills, and those in Austria, Germany, the United Kingdom and France, predict their future energy

## Productivity



needs within their own mill systems

3 The control center systems in Jämsänkoski and Augsburg then collect and consolidate the mill-wide consumption and production histories and forecasts.

The mill systems predict both electric power and steam consumption. Natural gas consumption is predicted at those mills that use it as fuel. Some mills include water in their balance calculations, since process water manufacturing is a key paper mill resource. Water and steam, however, remain mill-internal issues and only the electric power and natural gas data are transferred to the control center.

**ABB's Energy Management and Optimization product is the result of state-of-the-art software technology combined with years of experience.**

The control center system compares the consumption forecast with available energy production capacity and existing purchase and sales contracts. It uses this information to help the control center staff place bids on the electricity markets in preparation for energy purchases and sales.

All of UPM's Central European electricity and natural gas purchasing is managed from the Augsburg control center. Due to the different electricity markets, and the difference in the energy supply structure of the company in the Nordic countries and in Central Europe, the systems in Jämsänkoski and Augsburg are not totally identical.

Pasi Svinhufvud was responsible for implementing the new energy management systems at UPM. "We try to save energy, and now have the tools to monitor energy expenditure in real-time. By keeping abreast of the situation, we can plan our operations to match our objectives. We use energy when it's cheapest and procure it from the sources that have the best market conditions for production," he said. "In the two energy control centers, we produce data on electricity and fuel market trends and forward it to the mills, thus enabling them to plan their own energy production. In return, we receive their generation plans, which allow us to manage the corporate energy balance. Mills that have extra electric power generation capacity can transfer it to the control center, which then either sells it to another mill or to the external electricity marketplace."

#### **UPM emissions trading in Augsburg**

Greenhouse gas emissions reporting and the trading of emission rights are

managed centrally at UPM. The Augsburg team trades emission rights on behalf of all the mills. The Jämsänkoski team plays a supporting role in the decision making and keeps emissions records on behalf of the Finnish mills. In a centralized system, the use of emission permits and emissions reporting can be managed cost-effectively, thus avoiding any work duplication.

#### **ABB's system implemented early**

ABB was able to implement the Central European energy management system two months ahead of schedule.

The updated Jämsänkoski control center and mill systems in Finland represent the fourth generation of ABB energy management systems at UPM. ABB's Energy Management and Optimization product is the result of state-of-the-art software technology combined with 20 years of experience gained in supplying hundreds of challenging industrial process information management systems worldwide.

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# Parallel pumping

IPC technology in parallel pump control

Li Jinguo

The desire to get more for less is pursued by almost everybody, from economists and production managers to householders paying their bills. Usually, marginal improvements require heavy investments. Major breakthroughs with short pay-back times remain a pipe dream.

Variable-speed drives, however, are a refreshing exception. Energy consumption and overall life-cycle costs of equipment are reduced significantly, permitting operators to run the same production with much less energy. This becomes all the more topical in view of high energy prices and the unacceptability of the energy-related emissions on the one hand, and the industrial requirements of fast-growing economies such as China on the other.

ABB's intelligent pump control (IPC) goes even further than harnessing the strengths of the individual drive. It links and coordinates drives in pumping applications permitting these to be operated to the highest levels of overall efficiency, achieving savings of up to 20 percent beyond that of "normal" drive applications. The high levels of redundancy obtained also assure the highest levels of availability.



Productivity

Generally speaking, AC drives are the most energy-efficient method for the control of pumps. ABB provides an optional software package for water-pump control in conjunction with its ACS800 industrial drive: intelligent pump control (IPC). In this application, every water pump is controlled by one drive. The power range of the drives can be between 0.55 kW and 5,600 kW (depending on the application). An example with three drives controlling three parallel water pumps is shown in 1. The adoption of communications between the drives (using fiber-optical cables) eliminates the need for an external PLC<sup>1</sup>, thus permitting energy savings, shortening repair times, and preventing blocking of the rotation of the water pump and jam (blocking of the flow).

The operation of a multi-pump system at efficient speed therefore offers potential for significant savings.

Energy-saving principles

Pump control using general-purpose drives is mainly implemented through the control of flow rate. As in many other variable-speed drive applications, this enables notable energy savings.

2 depicts the head of a pump in function of its flow rate. The curve 2a traces the head-flow characteristic at pump-rotation speed  $n_1$ . 2b shows the same at a reduced rotation speed  $n_2$ . 2c shows the characteristic of the pipe resistance and 2d the characteristic with an increased pipe resistance (achieved with a valve constricting the flow).

With the pump running at the rotation speed  $n_1$ , and the pipe resistance set to its lowest value 2c, the working point of the pump is at A (intersection of 2a and 2c). The output flow rate  $Q_1$  is maximal and the power  $P_1$  applied to the shaft is proportional to the area  $Q_1H_1$ .

If the flow rate must be reduced from  $Q_1$  to  $Q_2$ , the traditional method is to change a valve setting, increasing the resistance of the pipe from 2c to 2d. The working point hence changes to B. This increases the pump lift from  $H_1$  to  $H_2$ . The power  $P_2$  now applied to the shaft is proportional to the area  $Q_2H_2$ .

If instead of a valve, a drive-control mode is used, the pipe resistance remains at 2c but pump rotation speed is decreased from  $n_1$  to  $n_2$ . The new head-flow curve is thus 2b and the working point moves to C. The pump head is decreased substantially to  $H_3$ . The power  $P_3$  applied to the shaft

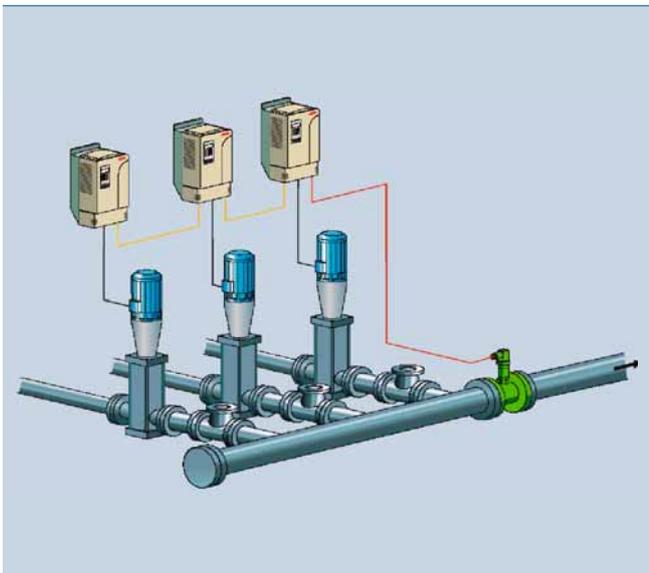
is directly proportional to the area  $Q_2H_3$ . This represents a reduction (compared to  $P_2$ ) proportional to the area  $Q_2(H_2-H_3)$ . The energy savings achieved will be similarly impressive.

Pump control using general-purpose drives is mainly implemented through the control of flow rate. As in many other variable-speed drive applications, this enables notable energy savings.

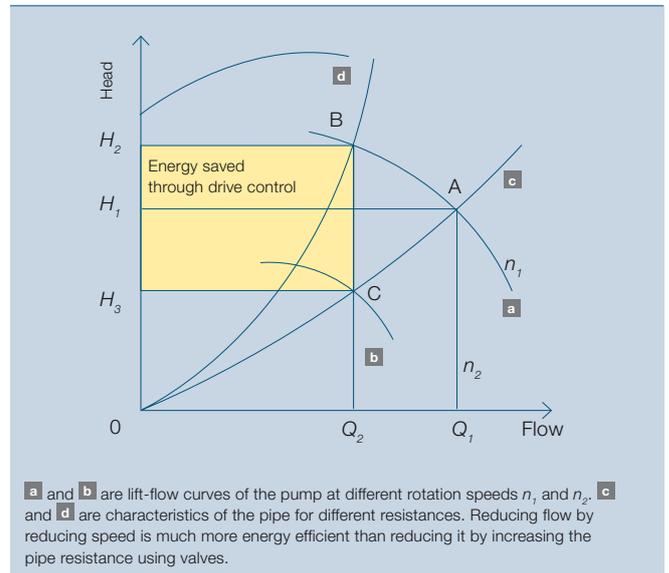
Efficiency of pump, motor and drive

The overall efficiency of a constant-pressure water supply depends on various factors. Normally, the larger the output power of the pump, motor or drive, the higher the efficiency of the system. When the same system is operated at a low speed, the overall efficiency of the system also drops. For a water pump designed to be operated in the 35 to 50 Hz range, the efficiency of the drive and motor system is about 90 percent at the rated operating point. This drops to 83 percent at 35 Hz. The efficiency of the water pump itself varies between 50 and 85 percent. Generally speaking, the efficiency of pump is affected by its speed and system curve.

1 Variable-frequency water-pump configuration: Optical fiber connections are used between the drives.



2 Power applied to the shaft is reduced significantly when drives rather than valves are used to control speed.



**Energy savings with IPC technology**

As an example, reducing the operating rotational speed of the water pump discussed above from 50 Hz to 45 Hz reduces flow rate by about 10 percent (see the formulae in the **Factbox**), therefore the time required to effect the same work is 11 percent greater. The power required, however, is 73 percent of the original power. As a result, electrical energy saved is about 19 percent  $(1-[0.73*(1+0.11)])$ . Although the overall efficiency remains similar, the energy consumption is reduced by a much larger margin.

If a product competes in the market only by relying on its sale price, its operating costs can be high.

When a water pump operates at efficient speed (in this case, 45 Hz), it delivers energy savings of about 19 percent. Energy savings of more

**Factbox** A background to pumps

The following explanation is mainly focused on centrifugal pumps, the most common type in water-pumping applications in industry.

A pump presents a square-torque load. In such a setup, the flow rate  $Q$  is proportional to the rotation speed  $n$ , the lift  $H$  to the square thereof and the shaft power  $P$  to the cube of the rotation speed.

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \quad \frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2 \quad \frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3$$

When a motor drives a pump, the shaft power of the motor can be calculated according to the following expression:

$$P = \frac{\rho * Q * H}{\eta_c * \eta_p} * 10^{-2}$$

where,

- $P$  power (kW)
- $Q$  flow rate (m<sup>3</sup>/S)
- $H$  full lift (m)
- $\rho$  fluid density (kg/m<sup>3</sup>)
- $\eta_c$  transmission efficiency
- $\eta_p$  pump efficiency

than 10 percent can be achieved in long-term operations with IPCs.

In practice, most systems use parallel pumps. If the traditional pump and fan control method (PFC) is adopted (one drive is used to power multiple water pumps), it cannot achieve the energy savings results of IPC technology.

As illustrated by **4**, the relationship between the efficiency, power, rotation speed, flow rate and lift of a system can easily be determined. In moving from working point A to B (upper diagram), the flow-rate is reduced by about 40 percent, on the other hand, power is reduced by about 60 percent (lower diagram). The operation of a multi-pump system at efficient speed therefore offers potential for significant savings.

The initial investment cost makes up a small portion of the total lifetime cost compared to the cost of electricity consumed in day-to-day operations.

**Life-cycle costs**

If a product competes in the market only by relying on its sale price, its operating costs can be high. If life-cycle costs (LCC) are considered on the other hand, the customer can reap tremendous economic benefits. For a water pump, motor and drive, these costs can be divided into three parts: initial cost, electricity costs and maintenance costs. **3** shows that the initial investment cost makes up a small portion of the total lifetime cost compared to the cost of electricity consumed in day-to-day operations. Cost savings focusing on this area can therefore return the greatest benefits.

**Multi-pump control modes**

Two distinctive types of control mode used for IPC are multi-pump control and water-level control. The multi-pump control modes can be further subdivided into:

- Master-regulated mode
- Multi-pump synchronization control

- Multi-pump reference synchronization control

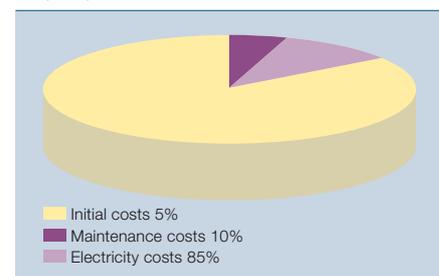
**Master-regulated mode**

In master-regulated mode, one drive is designated the master drive. The pumps attached to the other drives are either run at full speed or are off. Only the master drive's output frequency is varied to match load changes **5**. Once the master has reached full speed, the next drive is started and takes over as master.

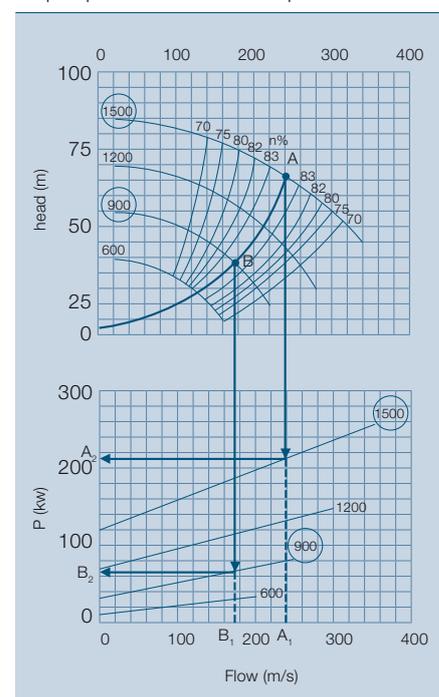
**Multi-pump synchronization control**

When pumps are operated with the multi-pump synchronization control method, all drives follow the reference of the master drive **6**. Starts and changes are synchronized.

**3** Energy costs constitute the largest part of a pump's lifetime costs.



**4** Flow-power and flow-lift diagrams for a pump at different rotation speeds



## Productivity

### Multi-pump reference synchronization control

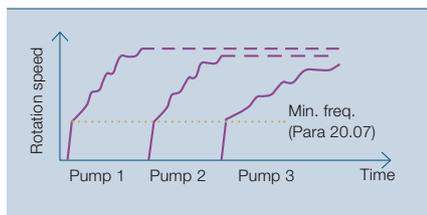
When pumps are operated with the multi-pump reference synchronization control method, all drives follow the reference of the master drive, but their starting times can be pre-set [7].

### Water-level control mode

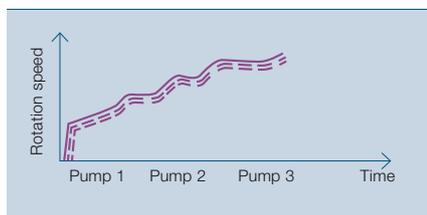
Water-level control is often used to control water tank filling or discharge. One feature, designed to prevent sediment from attaching to the inner walls of the water tank, involves changing the water-level according to a pattern set by the user. This creates a washing effect that keep pipes clean while operating pumps at suitable points on the efficiency curve. Water-pump control can not only be applied to a single pump but also to in two or three parallel pumps.

The control method is shown in [8]. The critical issue is permitting the pumps to operate at an efficient speed (for example, 45 Hz) to as large a degree as possible. If the water level changes, demanding a much larger flow rate, additional pumps must be

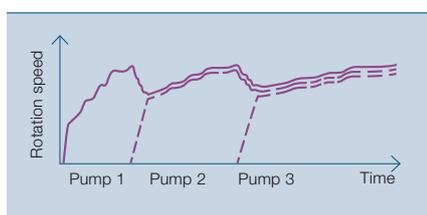
[5] Multi-pump master/slave control



[6] Multi-pump synchronization control



[7] Multi-pump reference synchronization control



switched on to permit the individual pumps to continue operating under efficient conditions. The example presented in [8] features three sets of pumps. The initial water level and efficient speed settings are adjustable in the control system, making it suitable for different demands and situations.

Using this method and according to calculations, energy savings of 10 to 20 percent are possible.

## The redundant setup of a multi-pump application makes it ideal for use in pump stations.

### Further advantages

#### Multi-pump redundancy

In traditional PFC mode (one drive controlling multiple water pumps), the failure of that one drive can cripple the system. As IPC technology features multi-pump redundancy, a single failed drive may affect the overall performance of the system but does not cause an overall system breakdown. Such a failed drive can be taken out of operation within 500ms, with the rest of the system continuing to operate.

Not just the drives themselves are redundant. Redundant connections, for example, reduce the impact of lost sensor signals. This ensures high availability and a low-risk operation of the system.

#### Anti-jam function

The anti-jam function allows a drive to perform preventative maintenance of water pumps, and clean them when they are blocked [9]. It can be triggered in three ways:

- Reverse rotation started when current exceeds preset limit.
- Time-triggered reverse rotation.
- Reverse rotation started by digital signal.

#### Water-pump priority control

The priority-based control function of the pumps helps optimize their operating times to permit more efficient maintenance schedules.

### Flow-rate calculation

Flow-rate calculation can be used in single-pump operation. In this situation, the drive acts as a flowmeter, enabling a sensor-free flow-rate measurement. This permits a dedicated flowmeter to be eliminated from applications in which flow-rate data is not required for billing purposes. Safety parameters can be defined for pressure control.

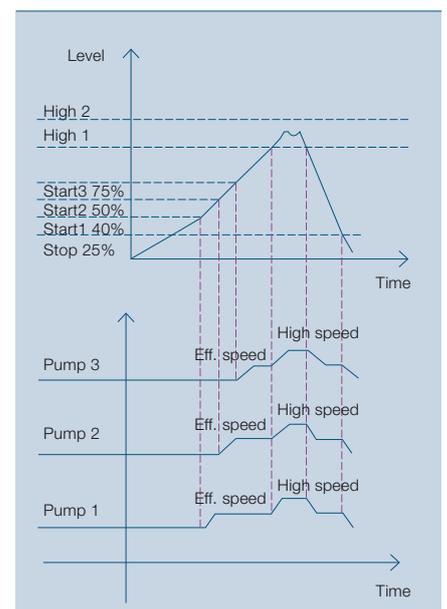
### Application examples in pumping

Two applications are presented here, a multi-pump application and a water-level control application.

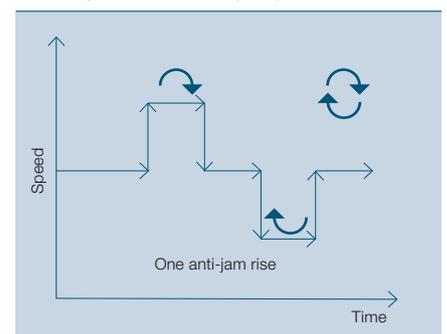
#### Multi-pump application

The redundant setup of a multi-pump application makes it ideal for use in pump stations. Communications among drives can be implemented via NDBU-95 DDCS [10].

[8] Control strategy of water-level control mode



[9] Anti-jam actions of a pump





**Water-level control application**

In a water-level control application, up to eight water pumps can be coordinated in the filling or emptying a water tank as shown in 11. The overflow switch and water level sensor are connected to the digital/analog interface (DI/AI). Any of these drives can be set as master and the start/stop water level in the master/slave setup can be customized.

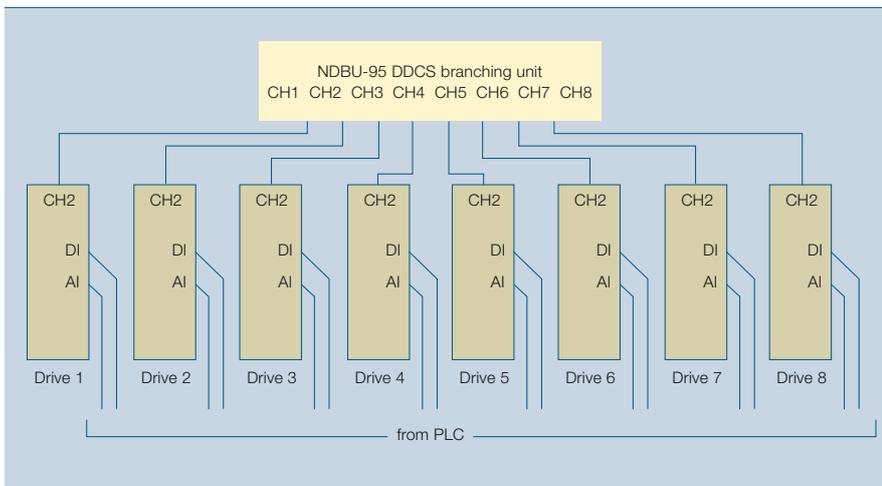
**A successful solution**

IPC has boosted energy efficiency and practicability in pumping applications. Compared to a rated speed of 50 Hz, at an efficient speed of 45 Hz, it can save about 19 percent of energy: Water pumps can achieve savings of about 16 percent over the equipment life-cycle.

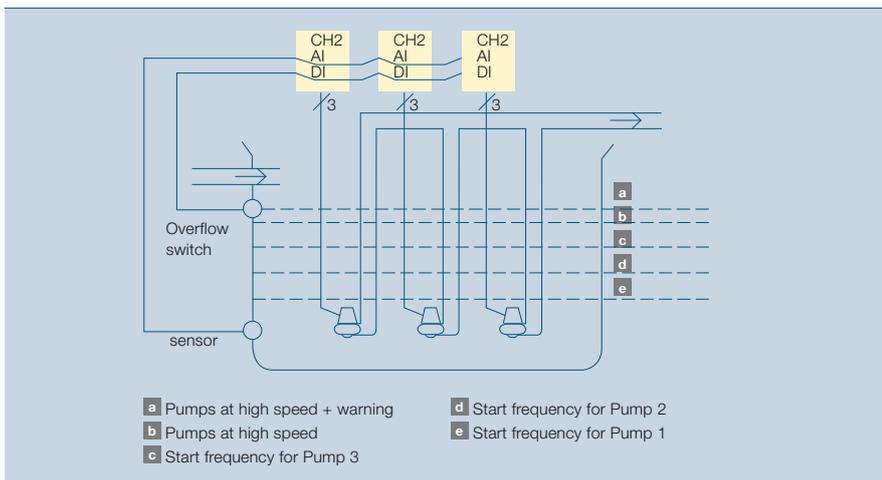
Two significant benefits are the system's 100 percent redundancy and the IPC's software with its anti-jam function and pump priority control that greatly reduce the risk of malfunctions in the water pump.

ABB's IPC technology in parallel pumping applications (particularly for high-power parallel pumps) meets the growing need for measures to save energy and reduce emissions.

10 Multi-pump macro control diagram



11 Water level control diagram



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**Further reading:**

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# With a human touch

How robots have learned to polish

Xianjie Bao, Wen Peng, Xingguo Yin, Xinyu Fang, Hui Zhang

An apparently simple operation to polish a work piece is in fact highly complex. A skilled person with a long experience in this process can do it very well and most of the handling is based on “feeling.”

China has developed into an industry for which polishing is an important step in production. The housings of mobile phones, computers, video cameras and similar consumer goods all need polishing before they can be used and China is a global center for the manufacturing of these parts.

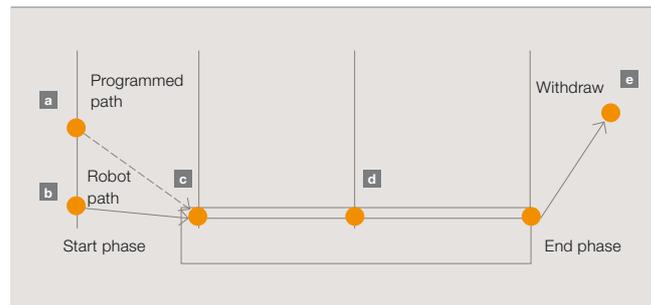
When we talk about almost one billion of those parts manufactured in China every year it is clear that even skilled workers cannot manage this huge amount of polishing.

With ABB’s new software tools, robots can learn this “feeling” required for high-quality polishing. Their flexibility and constant optimal performance make robots an irreplaceable tool for the computer, communication and consumer electronics (3C) industry.

In recent years, the 3C industry has grown continuously and China's mobile phone industry is a good example of that. The total shipment in 2007 reached more than 636 million units, up 24 percent over 2006. Similar growth is expected in 2008. With this rapid growth, polishing as a part of mechanical finishing in die-cast light alloys gains more and more attention. Polishing can be, and traditionally is done by manual work or by dedicated polishing machines. Now, robotic polishing is also being introduced as a new technology, which offers higher flexibility compared with manual polishing, and better economics than the use of dedicated machines. Replacing the manual work and dedicated polishing machines with robotic polishing can give the operators reprieve from the harsh environment and improve quality and efficiency while reducing cost.

Manual polishing requires highly skilled and experienced workers, increasingly difficult to find, as fewer people are interested in the "dirty" polishing environment. To reach consistent quality when shifts are changing and workers' skills are varying is very demanding. The introduction of robotic automation to such processes not only alleviates the stress on workers but also guarantees high quality throughout the whole manufacturing process.

1 Phases for the Controlled Contact Force model



In the 3C industry, aluminum and magnesium alloys are the most common materials for the decorative parts that do not require dimensional accuracy, such as mobile phone covers, laptop covers or mp3 covers. Factories face the challenge of frequently changing parts, which raises the request for high flexibility, a clear advantage of robotic polishing.

But before robots can do this work with the "human touch," they must learn a number of techniques, which, in the language of robots, result in offline as well as online programming, now developed by ABB.

**Sensitive robots need force control**

The key issue for a good finishing quality is to control the material removal rate in the polishing process. With a given polishing fixture, the material removal rate can be controlled by the speed and contact force of the polishing tool. Controlling the speed is relatively easy but traditional robot position control is not sufficient to guarantee a stable contact force.

In the 3C industry, the most commonly used light alloys have a low surface rigidity. In this case, to obtain fine quality requires an accurately controlled contact force of the robotic surface finishing system. ABB's new Controlled Contact Force model makes robots sensitive to contact forces; the polishing pressure can be "felt" by the robot and the surface of the

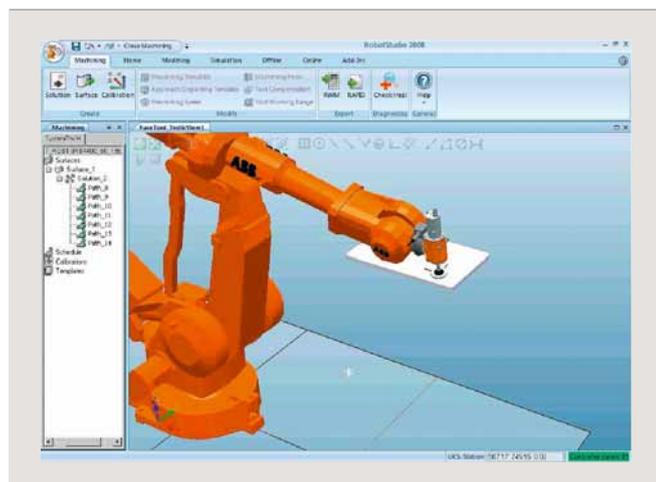
processed part can be followed to obtain the required pressure on the object.

The total shipment of parts from the 3C industry in China reached 636 million in 2006.

This means that the position of the robot will be adjusted to apply a constant force/pressure on the surface, even if the exact position of the surface is unknown. Since pressure is obtained by moving the robot path, this parameter is suited for polishing, grinding and cleaning, where a surface should be made even and smooth. The removed material and the subsequent changes of the surface topology are dependent on a number of process parameters like tooling, applied pressure or robot speed, for example.

The phases for the Controlled Contact Force model are described in 1.

2 RSMPP graphic user interface based on ABB RobotStudio



3 RWMFC graphic user interface on the Flex-Pendant of IRC5 controller



## Robotics

During the start phase, the robot is switched to the force control mode and moves in the direction of the reference force in order to get in contact with the work piece **1b**. Once a contact is achieved the robot will start the movement towards the programmed position **1c**. During the process of moving along the surface, the robot will still be kept in force control mode. After the last process movement, the robot is removed from the work piece and switched to position control mode when moving to the end position **1e**. With a controlled contact force, the material removal rate can be kept constant during the polishing process and the required finishing quality is obtained.

### Offline and online programming

ABB's force-control technology provides a well-defined value of the force applied to the work piece, but as a force is characterized by its magnitude and direction, the robot path needs a control as well. Most abrasive tools have a specific abrasive working surface, so that a different contact tilt leads to different polishing effects. To obtain the best quality, the abrasive tool has to keep both a stable contact with the work piece and the correct tilting angle along the polishing path.

In the 3C industry, a lot of decorative parts that need polishing have very complex shapes. To program a robot to follow these paths is a big challenge. Traditionally the path is programmed by hand when the coordinates of the path are determined by a worker. But an accurate polishing path on complex curvature surfaces requires hundreds of coordinates for the contact point, the tool orientation and the tilt of the tool.

ABB has developed two dedicated software applications for robotic machining to solve this complex problem. The CAD-model-based offline programming environment called RSMPP (RobotStudio Machining PowerPac) is a module within ABB RobotStudio **2**. RobotStudio is a PC-based software, which provides virtual robot

system support, offline programming and simulation in a 3-D environment. Based on this platform, RSMPP develops key functions as CAD-based path generation, machining-process template based programming, and exporting of the generated programs.

The online software product called RWMFC (RobotWare Machining Force Control) is based on the ABB IRC5 robot controller, and is a special option to support force-control-based robot machining applications. The key functions of RWMFC are online teaching, auto-path learning and exporting the program with its defined path parameters **3**.

### Robot polishing provides more stable finishing with increased productivity.

With the combination of CAD-model-based offline programming and online auto-path learning, accurate polishing can be provided. Based on the CAD model, by choosing the right polishing template, RSMPP generates the paths. The result can be tested in both a 3-D simulation or the real robot system.

If no CAD model is available, the user can use RWMFC to define rough outline points by leading-through with force control. Auto-path learning can then be performed by the robot system itself. With high accuracy, missing coordinates can then be added to the

generated path. It is also very common that the CAD model shows small differences compared with the real part. When these differences affect the polishing quality from an offline-generated path on the real part, online auto-path learning can be applied based on the outline points generated by the offline RSMPP. **4** illustrates the functionalities of these software solutions.

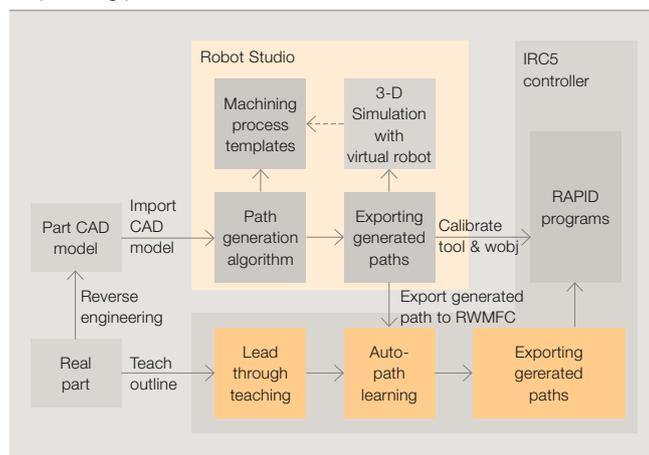
The ABB software solutions for automatically generating polishing paths not only improve the processing accuracy, but also introduce great flexibility for robotic polishing applications. When parts change, which happens very often in the 3-C industry, the time spent in re-programming robot can be shortened significantly.

### Aluminum alloy LCD back panels

A typical case for a polishing work in the 3C industry is an aluminum alloy LCD back panel. The surface is a spherical area (marked in green in **5**) on top of a square frame. Some scratches on the surface, probably generated in previous process steps, have to be removed before sandblasting and plating. In this typical mechanical finishing operation, a widely used medium-hard non-woven disc can be used to provide a proper material removal rate and surface finish. A CAD model and several test pieces are available to develop the applications.

As by position-control only at medium speed, a stable contact cannot be guaranteed, force-control is the right choice in this case. It is too time consuming to define the accurate polishing paths on this large part by hand; up to thousands of coordinates have to be defined. To provide a consistent surface finish for each part of the spherical area, the abrasive tool must contact the surface everywhere with a particular angle, which requires the tool orientation to change along the paths. Based on the CAD model, offline programming can be used to generate the machining paths for the pol-

**4** Using RSMPP and RWMFC to automatically generate the polishing path



ishing process using the cutting plane method. **6** shows a 3-D simulation of the extracted polishing paths in RobotStudio, with different tool orientation depending on the surface curvature.

The generated coordinates are downloaded to the IRC5 controller. Now the path can be tested in a real environment. In this test, one may find that some polishing areas between the scratch gaps on the panel are not polished as well as the other areas.

This is a result of the die-casting process, which has introduced more deformation on this area than described in the CAD model. To overcome this deficiency, the online path learning based on the offline generated paths are applied to improve the contact stability. The corrected and fine adjusted path is now used as a reference for the auto-path learning function. With this new path, the test is repeated and leads to an acceptable finish quality of the work piece. With the combined effort of both offline programming and online path learning, the best fit process with several hundred coordinates is obtained in a short time.

After generating the accurate polishing paths, additional tests must be

carried out to determine the factors that will influence the cycle time, tool wear and final finishing quality. These factors include the abrasive grain size, media hardness, abrasive tool diameter, spindle tilt angle and contact area. The result after these tests is a compromise between the final surface finishing quality, the polishing cycle time, the material removal and the abrasive tool-wear rate.

In comparison with the replaced manual polishing for this LCD back panel, robotic polishing provides more stable finishing quality with increased productivity.

#### The way forward

Robotic polishing in the 3C industry is a new application area for industrial robots, which so far seemed too challenging to enter. ABB, after developing the key required technologies – force control, CAD-model-based offline programming and online auto path learning – has paved the way to a broad implementation of robot polishing.

ABB is dedicated to further developing this attractive application by modeling the process parameters that, in addition to the robot performance, have an influence on the polishing task. A better understanding of these parameters will lead to a further in-

crease in automation of a flexible robot polishing process, reduce engineering time, lift the quality and reduce the cost.

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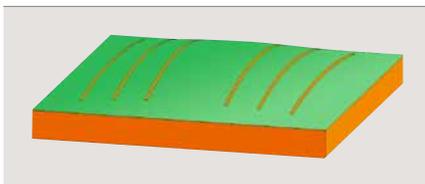
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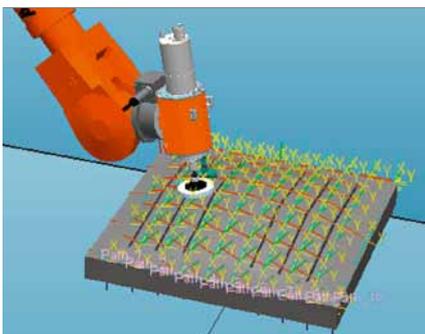
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**5** The CAD model of an LCD back panel



**6** Generated paths in RobotStudio 3-D simulation



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# Virtual engineering I

Intuitive offline programming for industrial robots

Liwei Qi, Xingguo Yin, Haipeng Wang, Li Tao

A new ABB robot simulation and offline programming tool has transformed a complex and time-consuming process into an intuitive and speedy exercise that can be performed during a sales visit to the customer. Designed for use by salespersons with limited engineering experience, the product has reduced robot simulation time from a typical eight hours to less than 30 minutes.



Conventional robot simulation and offline programming tools are usually designed for skilled engineers rather than for sales personnel whose engineering background may be limited. From a salesperson's point of view, existing simulation and offline programming tools are difficult to use. They require knowledge of geometric modeling, the ability to generate and adjust robot targets and paths, perform path configuration, position cell objects and so on.

ABB has identified the major bottlenecks that prevent robot simulation and offline programming from being intuitive and easy to use.

The usual solution to this predicament is for an engineer to create a 3-D simulation of a robotics cell on the salesperson's behalf. A simulation takes several hours to create, often a whole day. When the salesperson returns to the customer with the simulation, a certain amount of reengineering is usually necessary. All of this takes time and adds to the complexity of providing the customer with a quick and satisfactory solution.

To simplify this time-consuming process, ABB has identified the major bottlenecks that prevent robot simulation and offline programming from

being intuitive and easy to use. The solution – RobotStudio Machine Tending PowerPac (MTTP) – enables salespersons and proposal engineers to quickly set up a simulation of a robotized machine tending cell which they can present to the customer on-site.

#### Removing the bottlenecks

The five bottlenecks that have prevented intuitive offline programming and simulation are geometric modeling, robot target and path generation, creating robot solution scenarios, configuring robot targets, and determining the optimal position of cell components.

##### Geometric modeling

The current method for performing geometric modeling is to use either a commercial CAD tool – like Pro/ENGINEER or SolidWorks – or the modeling module of a robot simulation program. There are several drawbacks to both alternatives:

- The competence threshold is high. At least several days' training is required in how to use the modeling tool, as is the necessary engineering experience
- Geometric modeling is a time-consuming process (even for a skilled engineer) that prolongs the initial stage of offline robot programming
- If the geometric model needs to be changed at the solution proposal stage, a new geometric model has to be created.

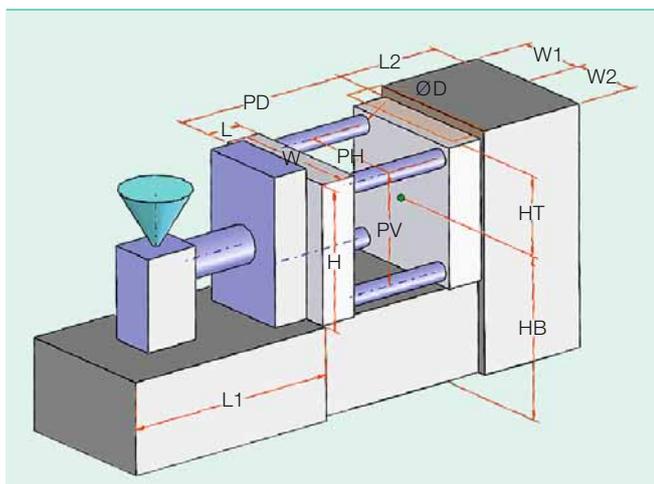
In order to lower the difficulty level and reduce the time spent on geometric modeling, ABB has introduced parametric-driven modeling. By analyzing various robotic applications, the devices for a robotized cell are categorized to form a device library. The geometric model of each device is standardized as one or several typical shapes.

■ shows a model of an injection molding machine with 13 driven parameters. Each parameter has a default value to ensure that models are created correctly. If the size of the model is not as desired, each parameter set can be changed separately or simultaneously to meet requirements. In this way a user can quickly and easily create a model of a complex injection molding machine without previous knowledge of conventional geometric modeling tools. And, by changing one or several driven parameters, a new model of the machine is immediately created. This can be used on any device in a robotics cell for which a 3-D geometrical model is required.

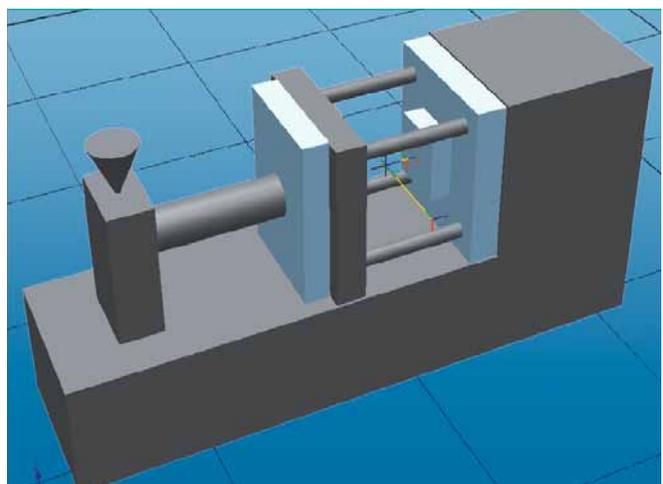
##### Target and path generation

The usual way to define the robot path is either to jog the robot to the target and record the posture (position and orientation) of the tool center point, or to input the value of the posture directly via the user interface. Either way is inconvenient and involves trial and error regarding the precision of the targets created. When

1 The parametric model of an injection molding machine



2 A geometric model and associated robot targets and paths



Robotics

all the targets have been defined, they then have to be organized into one or several paths. This involves defining the order and the properties of each move instruction – speed, tool data and whether, for instance, it is a linear or joint move. This is also a time-consuming process that demands extensive robotics knowledge and the skills to use a robot offline programming tool.

To reduce the complexity of target and path generation and integrate the procedure with process requirements, ABB has developed an automatic robot target and path generation method based on a parametric-driven model. The method is not limited to machine tending applications.

The machine tending application comprises various devices such as machines and conveyors. These devices can be defined as workstations that include a geometric model and two or more robot targets that form one or more paths. There is a connection

between the geometric model and the target posture of the robot. For instance, the picking point for a molded part is always in line with the center point of the molding plate. By formulating algorithms of the relationship between a robot target and the geometric model, target generation becomes automatic. Furthermore, the specific application needs of robot targets and paths can be organized as templates. Each template defines the order of targets in a path, the motion properties of each robot move, and so on. The template enables a robot path that is well matched with application needs to be quickly generated.

Machine Tending PowerPac (MTPP) is fully integrated with ABB’s offline programming and simulation platform RobotStudio.

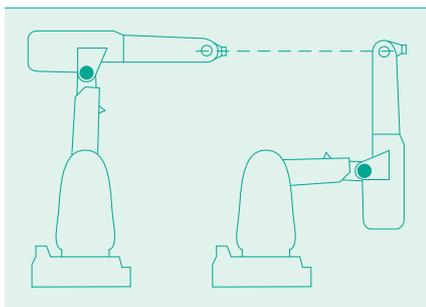
process template. If the size of a workstation needs to be changed to accommodate application needs, a new geometric model can be easily created by changing its driven parameters. The targets, which belong to the workstation and are part of the geometric model, are automatically updated.

Scenario-based robot programming

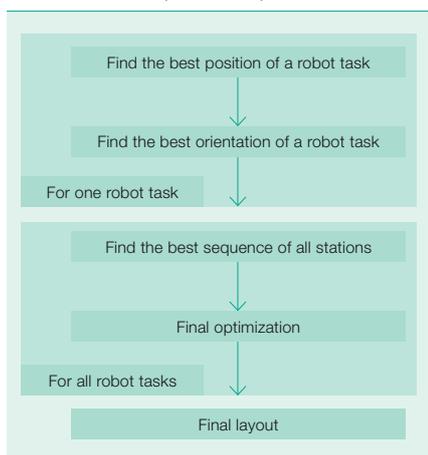
To provide an optimal solution for a customer it is necessary to prepare, compare and evaluate different scenarios. An example of a scenario for an injection molding machine is picking a part from the front of the machine; another example is releasing a part to the machine, then picking a new molded part from the top of the machine. A scenario is made up of robot motion, tool methods and station logic. Robot motion involves robot paths, tool methods involve tool data and tool signal logic, and station logic encapsulates station signal handling.

The conventional way to create different scenarios is to copy the station model and create another set of robot targets and paths manually, as well as the tool methods and station logic settings. Again, this is a time-consuming operation. The ABB solution is scenar-

3 Two different arm configurations when a robot approaches a target

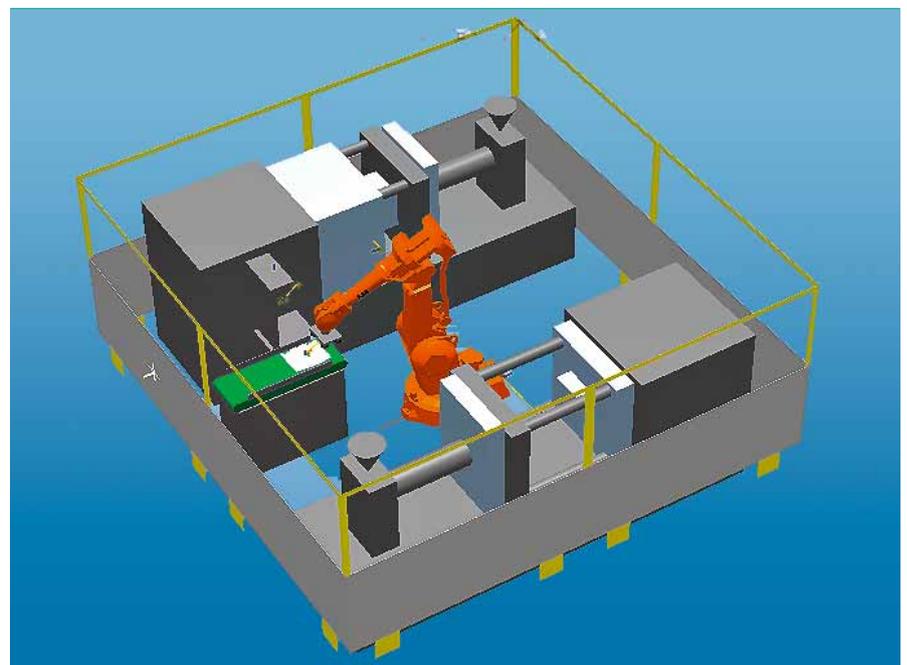


4 Flowchart of optimal cell placement



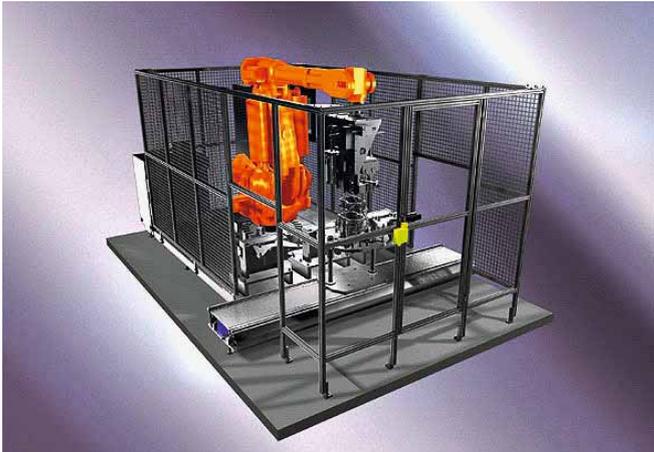
2 shows a geometric model and associated targets and paths. Robot targets are created from the same set of parametric-driven parameters as the model in figure 1. All robot targets are organized into two paths (one in-path and one out-path) in accordance with the

5 Optimized machine tending cell created in Machine Tending PowerPac



io-based robot programming. The method not only automatically generates the geometric model and robot targets and paths, it also enables a geometric model to be mapped with different sets of targets and paths from different scenarios. This makes it easier and faster to switch and compare different layouts (scenarios) for an application solution.

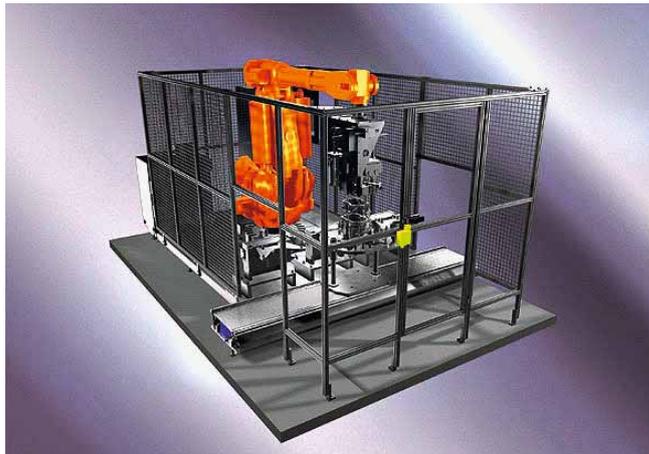
#### Target configuration planning

It is usually possible to attain the same robot target in different ways by using different sets of axis angles. These are known as robot configurations.  shows two different robot arm configurations that both attain the same robot target. The configuration on the right attains the target by rotating the robot arm backward and rotating axis-1 180 degrees.

The fact that the robot can reach two targets does not mean that it can traverse a path between the two targets. That depends on the rotation limits of the axis when the robot is moving. Since in most cases there is more than one configuration option for a robot target, this raises the issue of how to choose the appropriate configuration data so that the robot traverses the entire path to reach the target. Furthermore, the configuration setting for each robot target should ensure smooth robot motion throughout a cycle (a cycle is the collection of paths that a robot will perform in a robot sequence).

MTTP is already proving of immense benefit to ABB partners and customers in machine tending and other applications worldwide.

In most offline robot programming tools, the configuration data for each robot target is defined manually. This takes time and requires a high degree of knowledge and skill from the user. MTTP, on the other hand, incorporates



a configuration planning algorithm for automatic target configuring to ensure smooth robot motion along a cycle.

#### Placement of cell components

Correct positioning of the robot cell components is essential to make good use of robot capacity and ensure maximum productivity from the cell. This requires a degree of knowledge and experience in robotics that is unusual in a salesperson. A solution for the optimal placement of cell components to achieve minimum robot cycle time is presented on page 90. A brief outline of the solution is given in .

Usually, more than one task is performed in a robot cell. Simply repositioning a robot task will not improve robot performance if it only involves a change in rotation of the first axis. Taking this into account, the positioning of several robot tasks can be divided into three stages: individual task positioning, task sorting, and cell optimization.

First, each individual robot task is considered separately to determine the best position and orientation relative to the robot. Second, the best order for the robot to perform the tasks is determined to achieve the minimum cycle time. Successful implementation of the first two stages provides the foundation of the third, cell optimization. At this stage, the position and orientation of the robot tasks can be adjusted simultaneously using a simulated annealing algorithm [1].

#### Simulations in minutes

Easy offline robot programming as described above is now possible with Machine Tending PowerPac (MTTP), which is fully integrated with ABB's offline programming and simulation platform RobotStudio . MTTP was launched in 2007 and is already proving of immense benefit to ABB partners and customers in machine tending and other applications worldwide. Designed primarily for salespersons and proposal

engineers, its comprehensive scope of benefits includes the following:

- Quick virtual cell creation and modification
- Previous experience of RobotStudio not necessary
- Estimates cycle time and cell footprint
- Instantly identifies the bottleneck within a production cycle

Reduced cycle time is being achieved by optimizing the layout of the robot cell and is discussed in the article "Virtual engineering II" on page 90 of this issue of *ABB Review*.

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#### Reference

- [1] ABB Research Ltd. (2007). Method for optimizing the performance of a robot. Patent number US 2007106421.

# Virtual engineering II

Optimal cell layout for industrial robots improves manufacturing productivity

Dandan Zhang, Liwei Qi

Recent ABB research on the optimal cell layout for industrial robots has reduced robot cycle times by as much as 20 percent compared with existing approaches. In automated manufacturing processes such as welding, painting, cutting and material handling, a robot always performs a repetitive sequence of operations along a predefined path. The productivity of a robot can be improved considerably by reducing the cycle time for completing an operation sequence. Robot cycle time depends on many factors, of which the position of the tasks that the robot is to perform is very important. Optimizing the layout of the robot cell can reduce cycle time significantly.

Much research has been carried out in recent years on the issue of cell layout. Basically, the methods proposed can be categorized as follows:

- Adjusting the position of the robot
- Optimizing the position of a task relative to the robot
- Optimizing the position of several tasks relative to the robot
- Redesigning the robot tool
- Optimizing the position of external axes relative to the robot or each other

Each of the above methods has a limited ability to deliver the optimal cell layout, especially when multiple sub-tasks are involved. Recent ABB research has focused on a three-stage approach to determine the optimal cell layout for a robot to perform multiple tasks in the shortest possible cycle time.

### Creating the optimal cell layout

The three stages of ABB's optimal cell layout method are: 1) individual task placement, 2) task sorting and 3) cell optimization **1**. During the first two stages alone a near-optimal layout is obtained in a short time.

In stage one, each robot task is placed in a "preferred region" to obtain good initial positioning; then, the most efficient ordering of tasks is obtained by using the switch method; third, the position of each task is adjusted simultaneously by means of the simulated annealing method to arrive at the optimal cell layout. In tests (presented below), the new method has achieved significant and impressive reductions in robot cycle time compared with existing approaches to cell layout optimization.

#### Individual task placement

Task placement consists of placing each task in a preferred region and rotating it along its own frame to arrive at the best position.

The preferred region is a concentrated area within the robot's reach in which most robot tasks are placed **2**. If a robot task is placed in the robot's preferred region, good robot performance and low cycle times can be expected.

Robot tasks are defined by targets. A target can be viewed as an infinitely small object with three coordinates defining its position and three angles defining its orientation in a three-dimensional Cartesian space. Changing the position of a task is the same as changing all targets used to define that task.

#### Task sorting

When the best position for each individual task has been determined, the question arises of how to sort all the tasks to obtain the best cell layout. Experiments have shown that the best position of a task will remain best when only the first axis of the robot rotates while tending that task. As shown in **3**, even if the task position is changed from Position 1 to Position 2, the task is still in the best position for the robot to tend. Task sorting is to find the best space sequence for

the tasks under a preset logical visiting sequence. To make rapid task sorting possible, a switched method was designed and incorporated into the solution **4**.

Suppose there are  $M$  tasks to be sorted. That gives a total of  $M!$  possible solutions for task sorting. If  $M$  is small, it is possible to search that space which has a dimension of  $M!$ . However, if  $M$  is large, searching the whole solution space is quite time-consuming. In this case, the sorting method switches to a simplified generic algorithm (GA) method to seek the best sequence of tasks, since GA is an effective optimization method for solving combinatorial optimization problems of large dimensions.

Recent ABB research has focused on a three-stage approach to determine the optimal cell layout for a robot to perform multiple tasks in the shortest possible cycle time.

Thus, if the total task number is  $M < M_0$  ( $M_0$  is a threshold), the best sequence will be searched for throughout the entire search space with dimension  $M!$ ; while, if  $M \geq M_0$ , the search method switches to the GA-based method to reduce the time spent searching.

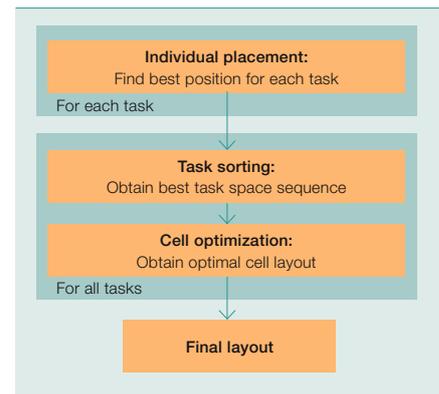
#### Cell optimization

At the cell optimization stage, the simulated annealing (SA) approach is adopted to determine the optimal cell layout for all tasks. After the first two stages of task placement and task sorting, a near-optimal cell layout has already been obtained, which reduces the search space for final cell optimization. SA was selected because it delivers incrementally refined solutions, which provide the user with choice and flexibility. That is, the user can stop the optimization procedure once they are satisfied with the solution provided.

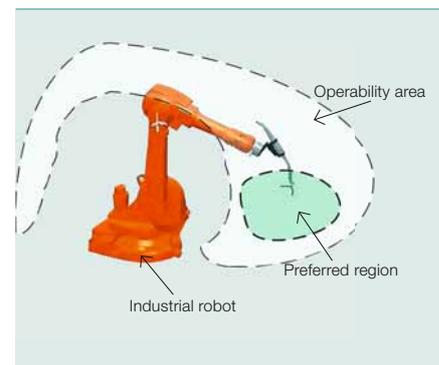
The simulated annealing method has been used to solve various combinatorial optimization problems. One of

its advantages is that the optimization process can start with a random layout. The user can specify an initial solution as the starting point to trigger the whole cell optimization process. The process can be stopped during

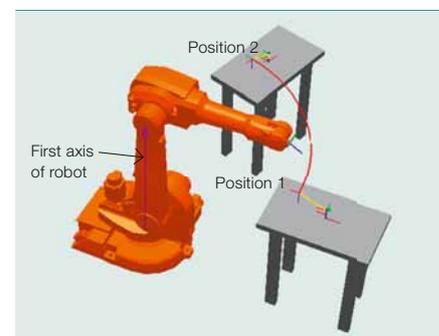
**1** Solution map of the optimal cell layout method



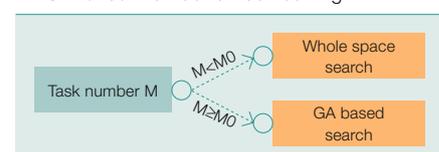
**2** Preferred region of the robot



**3** Equivalent positions of a task relative to the robot in terms of cycle time

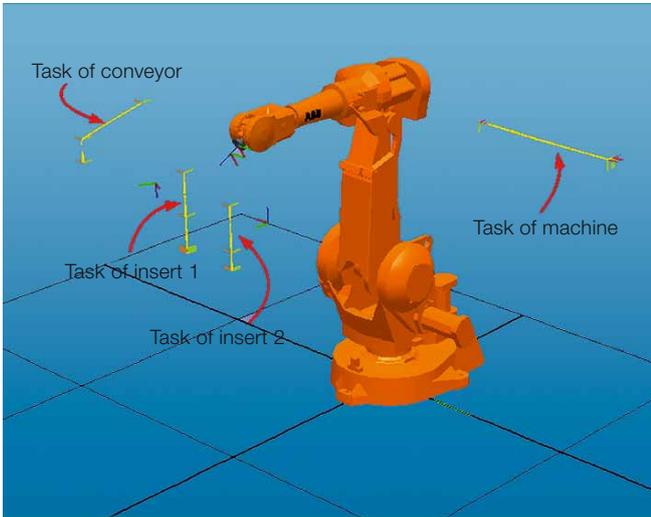


**4** Switched method for task sorting

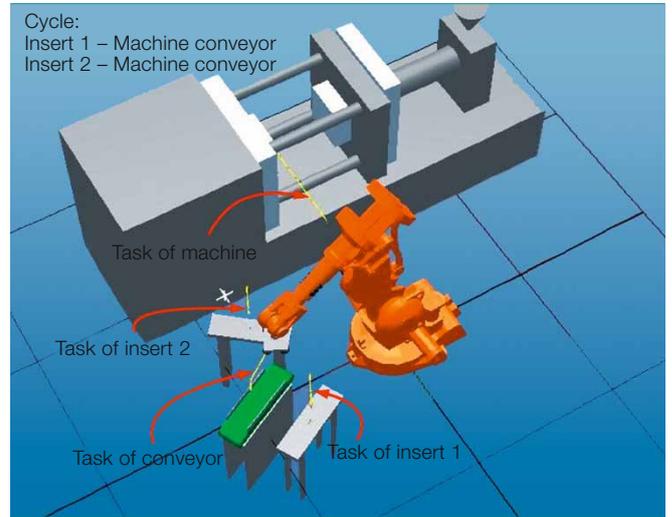


5 Machine tending test case

a Actual cell layout and task positions



b Optimized cell layout and task positions



algorithm execution with an intermediate result, and resumed with the intermediate result as the new starting point. This gives the user flexibility.

**Significant reductions in cycle time**

Significant reductions in cycle time have been achieved in tests in several applications – two spot-welding cases, one polishing and one machine tending case. Each experiment was performed using RobotStudio, ABB’s robot simulation and offline programming software.

Significant reductions in cycle time have been achieved in tests in several applications – spot welding, polishing and machine tending.

In the two spot-welding cases, the robot was required to visit each spot point to perform a welding operation. In spot-welding case 1, the welding points were in alignment; while in spot-welding case 2, the welding path was in an irregular shape. The results were compared with tests using the polynomial fitting method to find the optimal task position. The results of both sets of tests are presented in 6, which shows that the presented method reduc-

es cycle time by 17 and 20 percent in the two spot-welding cases.

The improvement in the polishing case was marginal (1 percent), as the robot task was simple to perform and already in a near-optimal position.

In the machine tending case, the cell consists of a machine for work piece processing, two insert stations and one conveyor. The cycle is composed as: Insert1 > Machine > Conveyor > Insert2 > Machine > Conveyor.

5a shows the cell layout before optimization, and 5b shows the cell layout after optimization. The results in 6 show a large improvement in cycle time of almost 13 percent. The productivity improvement was achieved by the new space sequence of the tasks (stations), and by the positional adjustment of tasks in the optimization procedure.

The experiments confirm that for tasks with complex paths that usually include several targets with different

orientations, the new method provides significant benefits; whereas for tasks with simple paths involving a small number of targets with similar orientations, the improvements in cycle time are marginal. This is because robot performance doesn’t vary much when the task is repositioned. The experiments also show that for the individual task, reorientation will always influence cycle time more than translation. For multiple tasks, task sorting followed by simultaneous adjustment is an effective way to reduce cycle time.

The success of the research and the size of the cycle-time reductions achieved have resulted in ABB integrating the method into its latest version of Machine Tending PowerPac (MTPP), which was released in September 2008. MTPP is an easy to use robot simulation and offline programming tool that reduces robot simulation times from a typical eight hours to less than 30 minutes, and can be used to create and present robot simulations by a salesperson during a customer visit (see page 86).

6 Test cases and results

Test cases	Existing method (s)	New method (s)	Improvement (%)
Spot welding 1	34.86	28.90	17.1
Spot welding 2	5.56	4.44	20.1
Polishing	30.70	30.40	1.0
Machine tending	21.90	19.0	12.8

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# A picture or a thousand words?

Graphic-based robot programming simplifies cell engineering

Jing Chen, Yongzhi Huang, Hui Zhang

Text-based robot programming for machine tending applications requires engineers to have a high level of robotics expertise. Alternative graphical-based programs require less skill but fall short in providing a clear graphical overview of the machine tending cell and robot movement logic. ABB is developing a solution to the problem with a fast and user-friendly graphical-based model for intuitive robot programming.



## Robotics

Machine tending cells are becoming increasingly complex. A typical work cell today consists of many stations – injection molding machine, conveyor, quality check station, scrap area, and so on. With so many stations it is not surprising that the 6-axis robot has become the robot of choice for operating these cells. However, programming a 6-axis robot is much harder than programming a linear robot. Application engineers are usually familiar with the machine tending process, but are less familiar with how best to integrate a robot into the process. A programming model that enables application engineers with minimal robotic skills to easily model the entire work cell and robot-machine interaction is clearly needed.

There are two main programming methods currently in use – manual and automatic. Manual programming involves text-based or graphical systems; automatic programming includes programming by demonstration (PBD). Text-based programming is especially common for industrial

robots as it offers flexibility for modeling the robot working environment. But robotics companies use their own BASIC-like robot languages, which limit the usability of text-based programs. Engineers have to learn the robot language of each robot manufacturer to be able to meet the vendor preferences of their customers. Recent research has, therefore, focused on developing general programming languages based on existing languages like C++ and Java. Even so, text-based programming requires the application engineer to possess a high level of robotics expertise.

Graphical-based programming requires much less skill in robotics than the text-based approach, although flexibility is sacrificed for usability. Flowcharts or graphs are popular in the graphical-based programming approach, and many application products with graphical or icon-based programming models are offered by robot suppliers. But they all share the same deficiency in that they lack a clear graphical method that expresses

robot movement logic and presents an overview of the work cell system.

With so many stations in the typical machine tending cell it is not surprising that the 6-axis robot has become the robot of choice in machine tending applications.

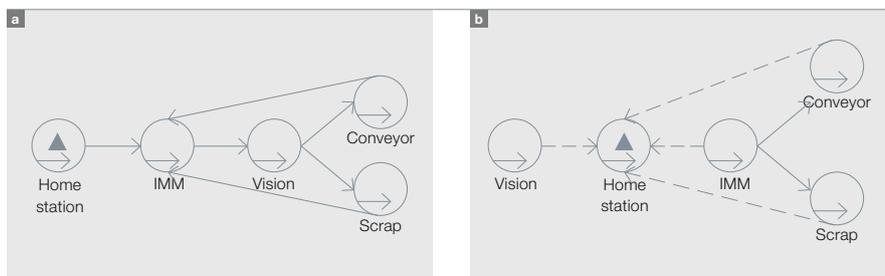
### Bringing clarity to programming

A typical machine tending work cell always contains many work stations. The robot is responsible for loading/unloading the produced part and for holding the part while moving between stations in accordance with the I/O (input/output) status of those stations. Work station, robot, robot movement, I/O interaction between robot and machine – these are the physical elements in the machine tending work cell.

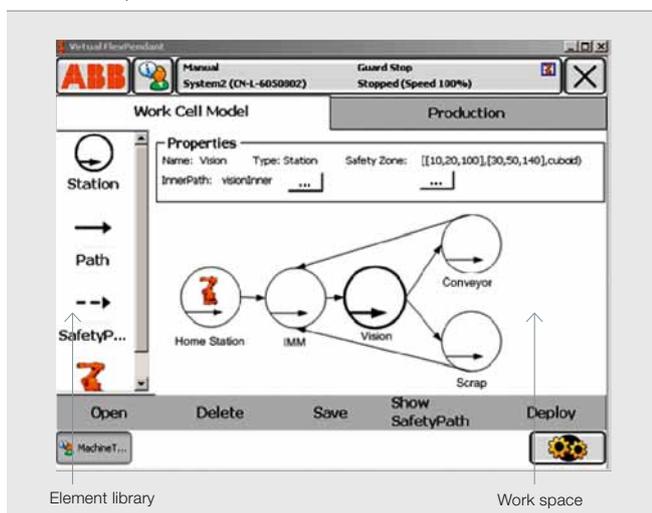
A typical example of robot movement and robot-machine interaction in a machine tending work cell is the following:

- 1 Robot moves to the position near the injection molding machine (IMM) and waits for the door to open
- 2 Robot enters the IMM when the door is fully open
- 3 Robot unloads a produced part from the IMM

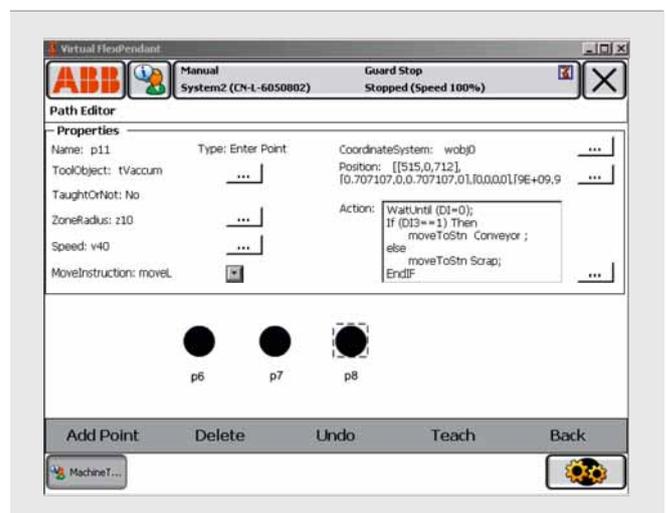
1 Production graphical model a and safety graphical model b



2 Work cell production model

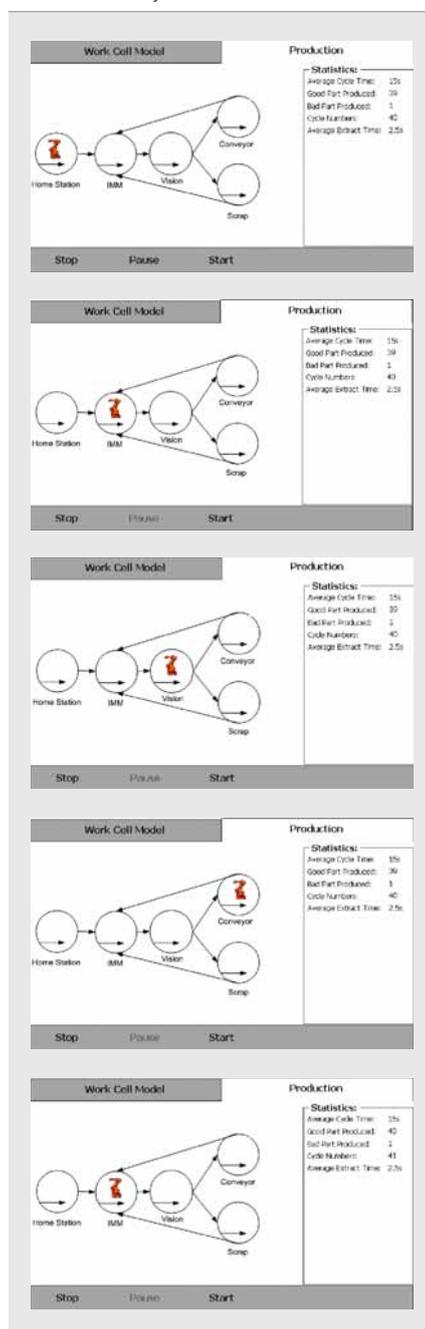


3 Path editor

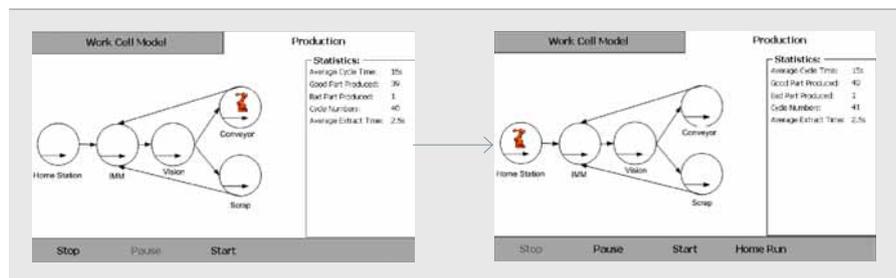


- 4 Robot exits the machine and signals the IMM to close
- 5 Robot moves to the vision station and unloads the part in the vision station
- 6 The vision station signals the robot to check the produced part. If the check suggests the part is a good one, the robot loads the part and moves to the conveyor and on to step 7. If the check suggests the part is a bad one, the robot unloads the part and moves to the scrap station and on to step 8

#### 4 Production cycle



#### 5 Homerun



- 7 Robot unloads the part onto the conveyor and returns to step 1
- 8 Robot unloads the part into the scrap station and returns to step 1

If a problem occurs during this sequence, everything in the work cell will stop. An operator then presses a button to move the robot to a safety position, or alternatively jogs the robot to the safety position. If all the continuous production cycles are finished – or if, for example, the robot requires maintenance – the robot will go to the safety position.

Existing graphical-based robot programming models lack a clear graphical method that expresses robot movement logic and presents an overview of the work cell system.

Graphical models of work cell production and the safety position are shown in **1**. These models form the basis of a user-friendly graphical interface **2** which includes an element library from which programming elements – station, path, inner path, safety path, etc – are dragged into the work space and configured. Clicking a dragged programming element reveals its properties. Similarly, in the Path Editor function, clicking a point will reveal the point's properties **3**. Actions bound with a robot target are triggered when the robot arrives at the robot target. The user can write rapid instructions to implement the branch motion logic. From here it is a short step to pressing the start button so that the robot will start pro-

duction according to the cycle configured **4**.

If the operator presses Stop, then the homerun button will be shown. If the operator presses Home Run, then the robot will return to the home station following the defined safety path, as shown in **5**. If there is no safety path defined between the station at which the robot stopped and the home station, the homerun button will be disabled.

These and other aspects of the graphical model outlined above are to form the basis of a new ABB engineering product for machine tending that will enable users to model the entire work cell area easily and more intuitively than ABB's current products, RobotWare Plastics Mould and RobotWare DieCast.

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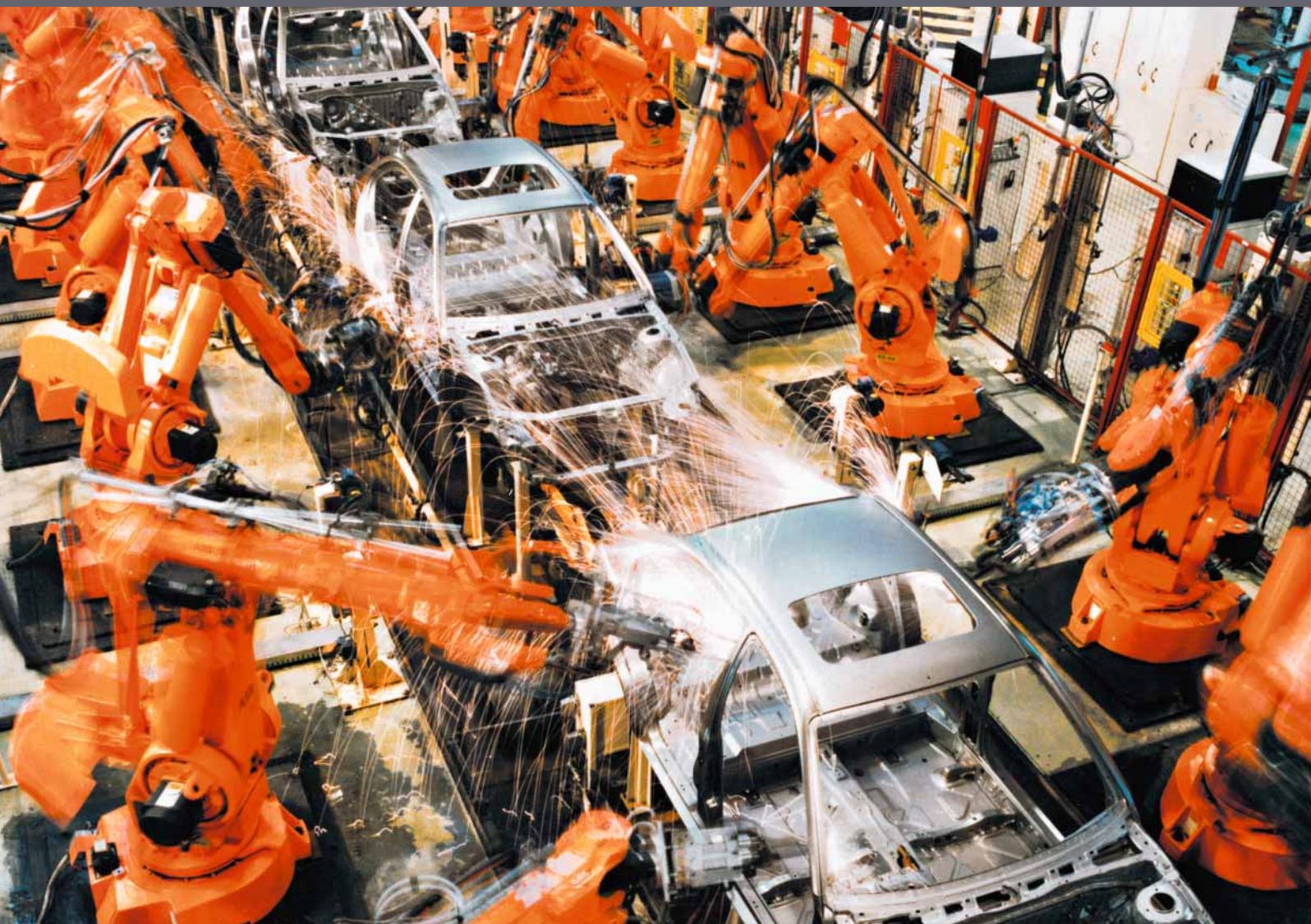
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# Hot-spot robotics

Improving productivity and quality in automotive spot welding

Bin Niu, Yonglin Chi, Hui Zhang



China recently surpassed Japan as the world's second largest automobile market after the United States. Annual output of automobiles is close to six million units a year. A key tool in automotive production is the spot welding gun and the industrial robot. One of the most important parameters of a spot welding gun is force tolerance. ABB is helping the Chinese automotive industry improve welding productivity and quality by developing new techniques for controlling force tolerance.

Resistance spot welding is widely used by the automotive and aeronautic industries as one of the major joining processes for sheet metal work pieces. Although many innovative technologies for sheet metal joining have been proposed in recent years, spot welding maintains its predominant status in body-in-white (BiW) assembly due to its low cost and high efficiency in automated production.

In recent years it has become increasingly popular to use a spot welding gun driven by an electric servo motor rather than the traditional pneumatically driven welding gun. This is due to its better welding performance and quality, which is made possible by the accurate control of the servo motor's position and torque. Major automobile manufacturers such as Renault, Mazda, Toyota and Ford choose servo welding equipment for their car body assembly lines instead of conventional pneumatic equipment.

Welding guns driven by AC servo motors tend to be mounted on the manipulators of articulated industrial robots and configured as external axes. They are controlled in a coordinated way with the innate six axes of robots. Control instructions sent by the servo controller, which is part of the robot controller, drive the servo motor at a velocity and torque predefined by the robot programs. The position and velocity of the electrodes are controlled respectively by the

quantity and frequency of pulses sent to the motor, with the clamping force between the electrodes dependent on motor torque 1, 2.

Precision control of the welding clamps improves the productivity and quality of the welding process greatly. Welding cycle time is significantly reduced by the fast torque of the servo gun in the squeeze phase. On average, it takes a servo gun only 8 cycles (0.16s) to reach the predefined pressing force; whereas for the pneumatic gun, it takes 30 cycles (0.6s) – a saving of 0.44s for a single spot. Multiply this by the thousands of spots welded in a car and the savings become immense. Cycle time is further reduced by the coordinated movement of the servo gun with the manipulator, which enables the gun tips to close while the servo gun is moved from one spot to another by the robot. Welding quality is also much improved.

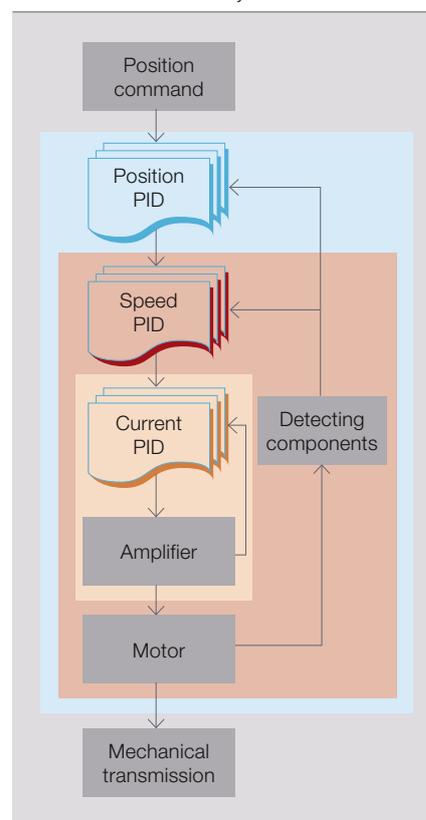
Despite its many strengths, the servo gun does have some limitations. It is well known that the most critical parameters for spot welding are time, current and welding force. Of these, the welding (electrode clamping) force with which the two electrodes press the sheet metal pieces together, is a key factor that determines welding quality. Although the force tolerance of the servo gun is much better than that of the pneumatic gun, the output force accuracy of the servo gun is still subject to some negative

influences. How to relieve or eliminate those influences to ensure that the predefined welding force is accurately executed on the work pieces is essential for welding reliability.

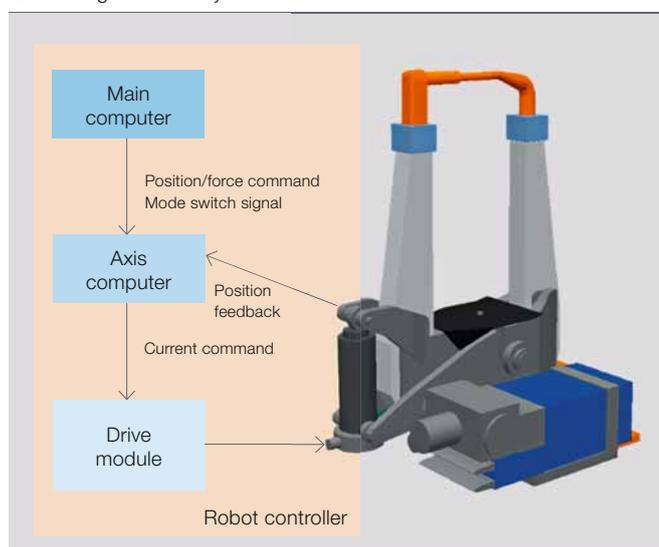
**Negative influences on the servo gun**

3 shows the output force of the servo gun in torque control mode and 4 shows the negative influences – tem-

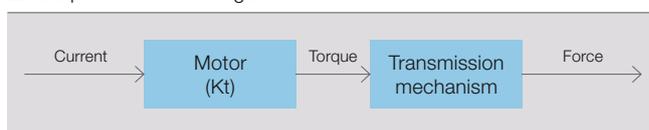
1 Servo motor control system



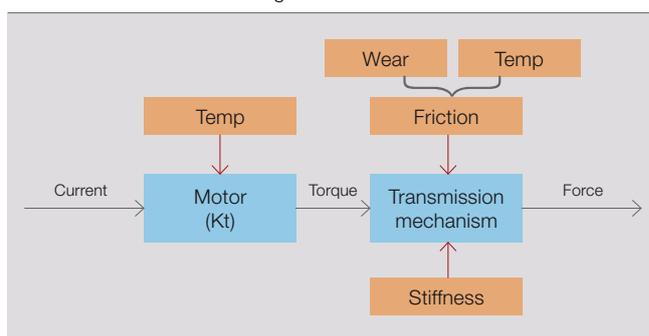
2 Servo gun control system



3 Output force of servo gun



4 Influence factors on servo gun



## Robotics

perature, wear, and stiffness – on the servo gun's output force.

### Temperature

Temperature influences the force flow in two respects and with opposite effects. Firstly, the temperature of the motor increases – due to the Joule heat generated by the welding current and the heat generated by the motor itself. Even if a constant current is supplied to the motor, the output torque of the motor will decrease and the output force will also decrease as a consequence. Second, friction loss in the transmission mechanism components, including the ball screw/nut mechanism and the arms, will be lowered by the rise in temperature, and reduced friction will result in increased output force.

### Wear

Wear and tear in the transmission mechanism of the servo gun is another factor that causes friction loss. After a period of use, a servo gun develops a more efficient transmission mechanism than a new one. This causes less energy loss due to decreased friction. Although a well-calibrated servo gun performs accurately when it is first installed, it often needs to be recalibrated after a period of time. Variations in the amount of friction in the mechanism can account for this.

### Stiffness

Stiffness in the mechanical arms of the welding gun can also cause deviations in output force. For instance, if the arm of the gun is too weak, it will bend when a relatively large force is applied to its tip. The greater the deformation, the worse the accuracy and linearity of the output force.

Various solutions that aim to enhance output force performance with improved accuracy are presented below. They are categorized according to whether the control loop is completely closed or completely open in relation to the target.

### Open loop force regulation

Although the driving current of the motor is regulated in a closed loop manner in the traditional control method of clamping force **1**, the transfer process from current to force

is left open. In other words, no force information is fed back to the axis computer for closed loop force regulation in real time. Solutions that regulate the clamping force on the basis of an open force loop fall into this category.

### Force feed-forward control

Feed-forward control is a strategy used to compensate for disturbances in a system before they affect the controlled variable. A feed-forward control system measures a disturbance variable, predicts its effect on the process and applies corrective action.

According to modern control theory, it is possible to estimate disturbance by a disturbance observer and remove it by the feed-forward control method so that the controlled target improves its immunity to disturbance.

### Temperature compensation

Small motors attached to servo guns tend to be more susceptible to temperature influence than larger motors. This has been solved by either using water cooling motors or larger motors that accept a higher force tolerance. But water cooling requires a more complex motor design and may cause water pressure to drop in the welding system due to leakage. Consequently, the current trend is to move away from water-cooled motors towards greater accuracy in force. This requires a better understanding of the influences on motor temperature and solutions that avoid the problem.

To realize temperature compensation in a servo gun control system, a temperature sensor needs to be mounted at a suitable position to detect the temperature of the servo motor or of the movable components of the welding gun. The sensor will send temperature information to the axis computer, where an adaptive temperature compensation function is integrated with the current control loop of the servo gun.

Results show that the relationship between variation in temperature and force is approximated by a linear function. Thus, a transfer constant can be used to represent the amount of force change per unit of temperature

change. After the target force is compensated in accordance with the temperature, a uniform pressing force can be produced without temperature variation.

### Periodic force checks and recalibration

Since clamping force is not regulated by closed loops, it is important that force precision is stable and that excessive deviation of force is detected as early as possible. Failure to ensure the timely detection of faults in welding clamps, or incorrect process parameters in resistance welding, can give rise to production waste or defective parts. Periodic checks or recalibration of direct force is absolutely necessary.

A good time to do this is when production is interrupted to re-mill the electrodes. In a BiW workshop the electrodes are typically re-milled after 400-500 spot welds, as wear gradually reduces the clamping force. By integrating a force sensor with the other tools and sensors at the service station, the force value can be sent to the axis computer. There, a program verifies how much the measured force deviates from the command value and determines if force recalibration is necessary. If so, an automatic calibration program is run to complete recalibration automatically.

Compared to the alternative and less efficient method of using a handheld sensor, servo gun malfunctions are detected earlier (which reduces waste) and force checks and recalibrations are performed automatically (which improves productivity).

**A hybrid dual-loop control strategy based on force and velocity is the ideal solution for servo gun control.**

### Closed loop force regulation

According to classical control theory, the control loop has to be closed on the control object to achieve accurate control of an output variable. But in resistance spot welding, it is not feasible to mount a sensor to the tip of the electrode for real-time force measure-

ment without interfering with the normal welding process. Therefore, alternative approaches to obtaining force information for closed loop regulation are necessary and a new control strategy is required.

#### Force measurement methods

In view of the infeasibility of mounting force sensors on the tip of the electrode, alternative methods for obtaining online force measurements have to be considered.

Force sensors can be mounted on other parts of the gun providing they do not interfere with the normal welding process and providing the sensor's output signals have a linear relationship with the clamping force. Alternative sensor locations are shown in 5.

A strain sensor can be fixed to a point on the robot arm (A) where there is a small, flat area offering good linearity and sensitivity between strain and force. The sensor measures the strain in the mechanical arms of the welding clamp generated by the clamping force. This is a low-cost, simple, but indirect method to obtain a force signal. Alternatively, a force signal can be directly obtained by integrating a piezoelectric force sensor with the spherical bearing between the drive motor and movable arm (B). A third option is to integrate a force sensor with the drive motor for better protec-

tion from the harsh production environment. It can be placed against the rotary-linear motion conversion mechanism inside the motor to measure the drive force (C).

However, feedback control without a force sensor is an attractive option. One such possibility, using disturbance observer control, estimates an external load from the current command and actual velocity of the motor and then feeds back the estimated torque to obtain a force feedback measurement.

#### Control strategy

With a force sensor in the solution, the control system should have its own force feedback closed loop in which the force error signal directly drives the amplifier and motor. But the servo welding gun, which is controlled by a robot controller as an external axis of a six-axis robot, is position-controlled in the same way as the robot axes. This means that force control loops can only be closed around position/velocity control loops. Moreover, in the welding process the control of welding clamps frequently switches between position control and force control. A hybrid dual-loop control strategy based on force and velocity is, therefore, the ideal solution for servo gun control. It offers better performance than single loop, and it is easier for a robot controller to close the force loop around a low-level position/velocity controller.

Despite the extra hardware and software, the servo gun with closed loop force regulation is set to become the preferred method in spot welding, not only because it improves force tolerance but also because a dynamic force profile can be easily realized for special welding cases.

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### ABB Review Special Report Dancing with the Dragon November 2008

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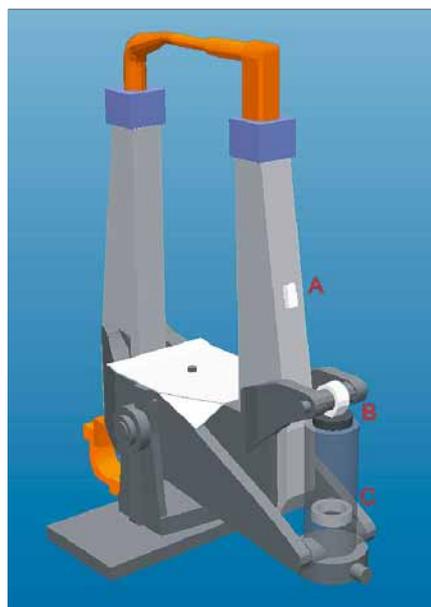
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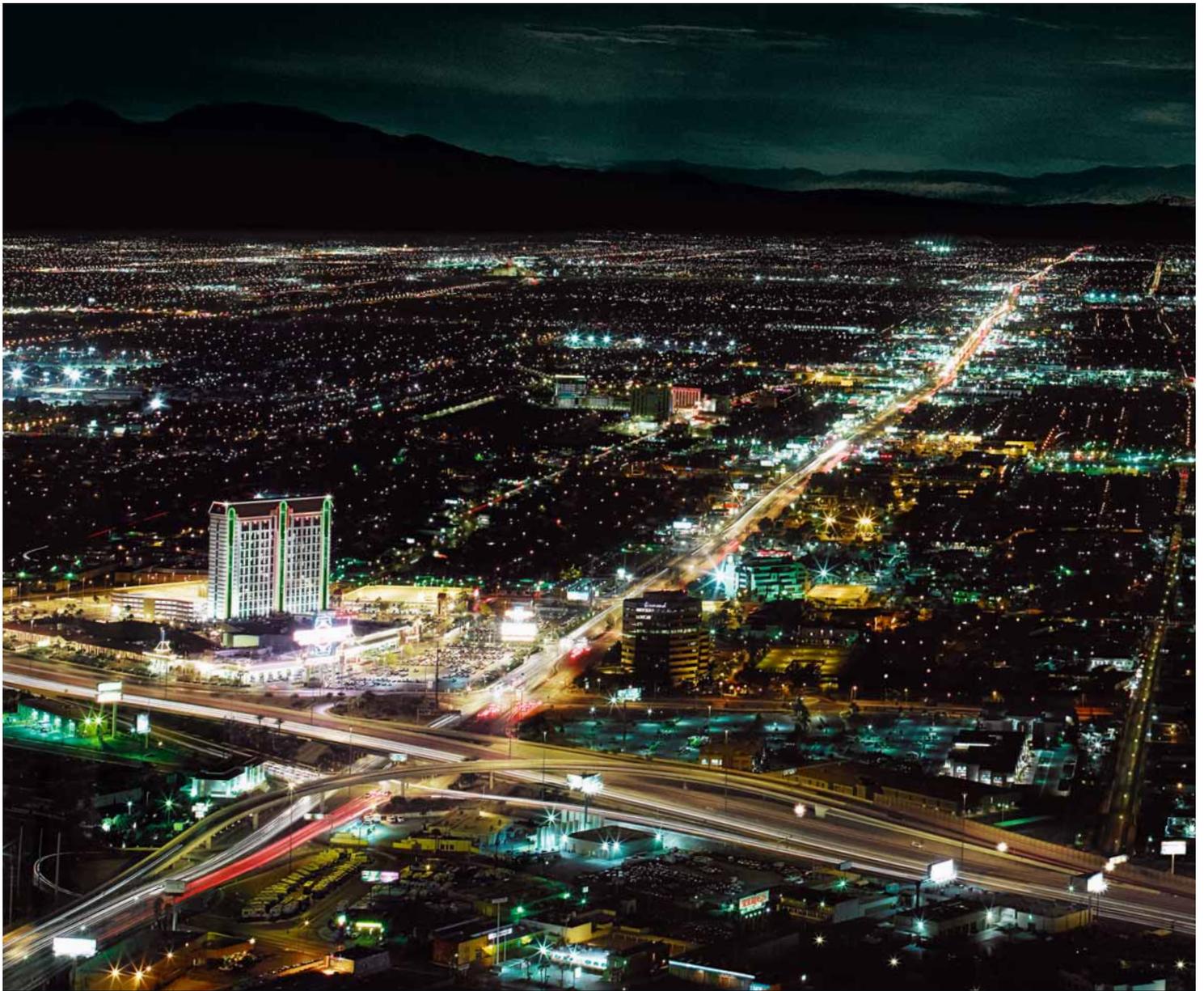
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5 Placement of force sensors on servo gun





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