ABB Review

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Green for growth

The traditional Asian rice fields that grace the front cover of this edition of *ABB Review* have ensured the survival of local communities for generations. Although greenhouse gas emissions are a matter of concern, the farmers who work these fields do so in a way that maintains and respects the basis of their production, permitting future generations to continue to use them. Like these farmers, society as a whole is the guardian of a fragile system. Besides optimizing profitability, businesses today must protect the elemental factors underlying their success: the environment and natural resources.

Sustainability matters

In the early days of industrialization, mankind enjoyed seemingly inexhaustible supplies of raw materials. The scale of activity then was small enough that the negative effects of waste or pollution could be disregarded. Anthropogenic effects on the environment have since grown to the point that the correlation between the usage of assets and their availability can no longer be ignored. Indeed even the clean water and air that we need for our survival cannot be taken for granted. Business leaders today must not only optimize the performance of their own companies, but consider the broader possible implications of their activities.

ABB's motto "Power and productivity for a better world" reflects our vision that our products and services must not only support our customers in their business objectives, but that these products are symbiotically embedded within the wider perspective of society and the world in which we live. Only by thinking sustainably and protecting the basis of our success can we assure its continuation. ABB's commitment to sustainability is reflected in the that fact that 50 percent of its corporate R&D budget is now being invested in energy-saving solutions.

ABB supplies many highly energy-efficient products. These reduce the carbon footprint of their applications by converting, transporting or using energy more efficiently than was previously feasible. Examples of efficient energy conversion covered in this edition of *ABB Review* include the new A100 turbocharger, and the BORDLINE® M converter for auxiliary traction applications.

ABB's variable-speed drives frequently feature among the company's flagship products in terms of energy savings that can be achieved. An objective environmental balance does not just focus on energy, but considers a wider range of aspects. An article in this edition of *ABB Review* shows that the overall environmental impact across the life cycles of these drives is also extremely favorable.

In a connected vein, a further article looks at how waste is being reduced through better recyclability of insulation materials.

The use of permanent magnets in large motors has long been an elusive objective but advances in magnetic materials mean that such applications can now be realized. Besides the savings in energy and complexity achieved by eliminating excitation equipment, the lower speed range that these motors can achieve means that gearboxes can also be dispensed with. Apart from the resulting gains in energy efficiency, this is also advantageous in terms of space, reliability, and life-cycle costs. Such arrangements are relevant to both industrial drive applications and generators in wind turbines.

Energy savings can also be achieved through improvements in the associated control concepts. cpmPlus Expert Optimizer helps run industrial processes efficiently. In another article, *ABB Review* investigates how software can be designed to support energy efficiency.

Not only are robots iconic for productivity, they are also a powerful sustainability tool. They can work in environments that would not be safe for humans, and furthermore the precision and repeatability of their actions leads to less waste. Most robot applications presented in *ABB Review* focus on ABB robots at work in customer facilities. An article in this edition takes a different approach and shows that ABB also uses its own robots – meet ABB robots that are hard at work making ABB motors.

I hope that these articles will give you a greater understanding of ABB's contribution towards sustainability and show how the ongoing efforts of the company are continuously leading to further improvements.

Enjoy your reading.

Peter Terwiesch
Chief Technology Officer
ABB Ltd.

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Sustainable results

Global energy challenges

An interview with Ernest Moniz addresses conflicting challenges that demand immediate attention

With an ever-increasing energy demand, rapidly depleting resources and a changing climate, the world is facing many challenges. ABB interviewed Ernest Moniz, professor of physics at the Massachusetts Institute of Technology and director of the MIT Energy Initiative, for his take on the global energy crisis.

What do you see as the main global energy challenges?
There is a perfect storm of three major challenges. One is around the whole issue of global supply and demand. We may be having a slowdown over the next couple of years, but this is a temporary response to the global economic downturn in terms of the greatly increasing future energy demand, driven in large part by the emerging economies. Electricity demand is the fastest-growing component of this and is expected to roughly triple from 2000 to 2050. But we should keep in mind that this increase represents not much more than raising the majority of the world's projected nine billion people in 2050 to what we would term in the OECD today a relatively low per capita use of electricity. In other words, there is a very real pressure for growth.

The second challenge, I would say, is the whole set of issues around energy security, including dependence on a few oil and gas suppliers and concern about nuclear proliferation. These issues are acutely felt, certainly by the populations of wealthy countries.

The third big challenge is the risk associated with climate change. This is, in my view, the most dramatic of the three challenges since we have a global energy system that is roughly 85 percent fossil-fuel dependent. So when we ask to have a major reduction of carbon use in a system that is mainly carbon based, we are obviously talking about a very dramatic transformation. Now why is it a perfect storm? Because there are inherently some tensions in the responses to these three challenges.

What is wrong with the strategy of continuing with business as usual and adapting as necessary when the time comes?
The remaining uncertainties that we have in understanding climate effects are a strong motivation to limit as far as rationally possible the accumulation of greenhouse gas. We face the big worry that we could experience significantly more abrupt, non-linear changes in our climate that drive us toward fairly catastrophic results. We need to push climate risk mitigation as hard as we can, recognizing that from where we are today, we cannot avoid a substantial measure of adaptation.

Do developed and developing economies face essentially the same challenges?
The obvious common challenge is climate change, in that it has a global impact. However, the nature of the impacts will be different everywhere. Deserts are expanding in China, and the Middle East faces severe water issues. We see a very dangerous reduction of snowfall and ice pack in glaciers in the Himalayas, and we often forget that the major water flows from the Ganges River to the Mekong River are driven by that. If you decrease these flows, can you contemplate the implications for over a billion people living in that arc?

There are opportunities as well. The developing countries will lag the developed countries in terms of a serious climate response, but the rate of growth of their energy infrastructures will be much greater, providing a greater opportunity to employ new technologies. But we have to make sure developing societies can afford these technologies. Change will take a long time, but if these societies develop their energy infrastructures using old technologies, then we are placing an even greater mortgage on the future.

So what do you see as the most promising strategies for tackling the challenges we've discussed?
The number-one target should be to increase energy efficiency in residential and commercial buildings – the proverbial low-hanging fruit.

Decarbonizing the electricity sector is very likely to be another major focus in the relatively near term. There are multiple opportunities, one of which is simply moving from carbon-intensive to less carbon-intensive fuels: coal to natural gas, for example. There's also the possibility of carbon

Factbox Professor Ernest Moniz

Ernest Moniz is professor of physics at the Massachusetts Institute of Technology (in the United States) and director of the MIT Energy Initiative, an institute-wide program designed to help transform the global energy system to meet the challenges of the future. He served as Under Secretary of the U.S. Department of Energy from 1997 to 2001. ABB and the MIT Energy Initiative formed a research partnership in 2008.

Global outlook

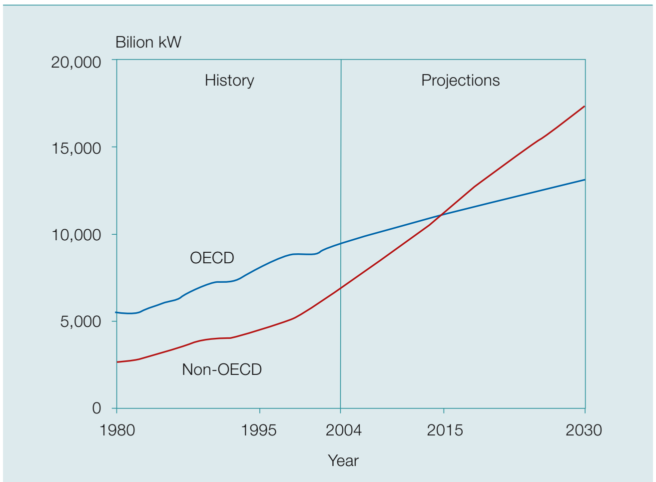
capture and sequestration in coal mines. The technology is yet to be demonstrated in a material way for commercial application, but it's an important option. Then, of course, there is a potential major expansion of nuclear power, which apart from hydro is the major non-carbon source today, providing a sixth of the world's electricity. In a few select regions, hydro may still have some opportunities; and then there are the other renewable sources of energy. Wind is beginning to make a material contribution, at reasonable cost in good sites, and solar is seeing rapid cost reductions and has very considerable potential. Improved electricity delivery will be an important enabler. So there are multiple technology pathways to address the issues in the power sector. The real issue is getting on with the job.

There's clearly a big role for policy in all these strategies, but how can the government help without trying to pick technology winners?
It's in principle fairly simple, although by observation apparently politically fairly difficult. First of all, a policy to incentivize lower carbon should do just that, and not pick the technology. Secondly, technology development and demonstration should be as technology neutral as possible. Choices must be made when funding demonstration projects, but we need to be funding much more aggressively a portfolio of projects that push us in the low-carbon direction.

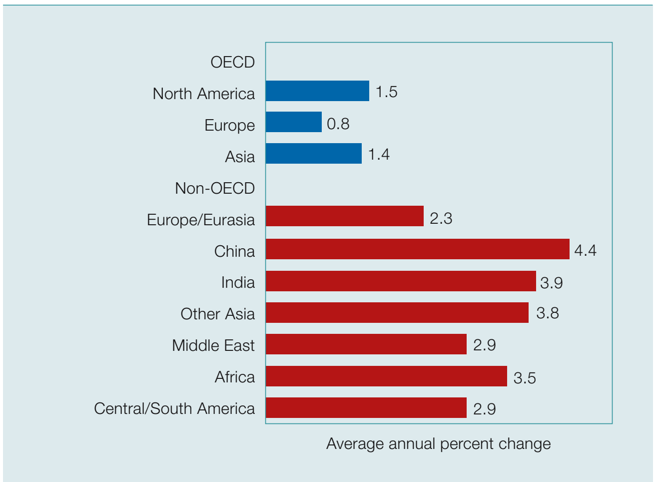
With technologies that we have in hand today and a dedicated program, we could have a dramatic transformation of the energy delivery system in a 10-year period.

Is a cap-and-trade system, which many markets seem to be evolving toward, sufficiently neutral to achieve the goal of carbon reduction?
A cap-and-trade system is in principle neutral if it really is an economy-wide cap, eventually with auction of the emissions credits. If you design an efficient system for gathering the revenues and returning the revenue to the population – payroll tax reduction, income tax reduction, check per unit of population – GDP should not suffer in any appreciable way. However, different regions and industries get hit in very different ways, and that inevitably leads the political system to consider how to compensate for these

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



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



impacts. It leads you away from carbon neutrality and from the most economically efficient system, but addresses the realities that any political system has to deal with.

Why is it that electricity demand has been rising so much faster than overall energy demand?
With electricity, there is enormous simplicity and cleanliness of use: You flip a switch and you get energy, and you don‘t have to do any fuel combustion locally. Electricity is also a very strong indicator of quality of life, so there is an enormous pressure toward modernization through the electrification of society. I'm not arguing that one should have a total electrification, but I think there is strong impetus and this underlies the fast growth. The US National Academy of Engineering designated electrification as the greatest engineering achievement of the 20th century with good reason.

The number-one target should be to increase energy efficiency in residential and commercial buildings.

So if demand for electricity is set to continue rising strongly, is our infrastructure able to cope?
Clearly we have inadequate infrastructure for the future. In the United States we are essentially working with a 50-year-old system that has many shortcomings, but this is where I think a new generation of energy delivery technologies can make a difference. For example, long-distance, high-voltage direct current (HVDC) grids level out the fluctuations caused by intermittent renewables, and information technology can be integrated with the grid at a much more sophisticated level. This will improve reliability and distribution efficiency. The technologies to accomplish this are fundamentally there. Sure, there are opportunities for additional research and development. But frankly, with technologies that we have in hand today and a dedicated program, we could have a dramatic transformation of the energy delivery system in a 10-year period. In the United States the new administration has come in with this as a very high priority, and I do hope that there is a clear national commitment to just go out there and do it.

There are multiple technology pathways to address the issues in the power sector. The real issue is getting on with the job.

That brings us to another point. What impact do you think the economic slow-down will have on the energy infrastructure sector?
The recession has already reduced energy prices and demand. The question is, will those factors lead us to repeat our mistake of the 1980s and revert to business as usual, once again delaying the job at hand? I think we can avoid much of that this time, largely because the populations of the world, including the United States, have become much more sensitive to the climate challenge. Large stimulus packages are being put forward in the United States, in Europe, China and India, and not surprisingly they are focused on near-term job preservation and job creation. In all of these countries, there is discussion of a substantial part of these packages being devoted to the growth and transformation of the energy infrastructure; and that's great. If done properly that will be a good investment and support jobs as well as our energy, security and climate goals.

Finally, if you were to embark on a career in the energy sector today, what area would you choose to go into?
First of all, I would start out with a strong grounding in science and/or engineering. I believe this is a critical foundation for having an impact on the system, and not just in a technology sense. Strong, technically grounded analyses at the intersection of energy technology and policy are a major opportunity to influence the system positively and are an important focus of our MIT Energy Initiative.

Interview conducted by Malcolm Shearmur, ABB Corporate Communications

For a better environment

Recycling opportunities for insulating components

Robert Sekula, Till Ruemenapp, Marlene Ljuslinder, Bernhard Doser

Power transmission and distribution utilities generate significant quantities of epoxy, silicone and porcelain waste products, especially during the process of renewing aging infrastructure. In the near future, the introduction of smart grid technology, while helping to create an energy-efficient power network, will inevitably add to this waste disposal problem, as old equipment is replaced with new. Currently there are no well-defined technologies that can be used to recycle insulating components that have reached the end of their useful life. This kind of waste frequently ends up in landfills.

With a view to reducing the impact of ABB's products on the environment and satisfying customers' requirements to fulfill ever tougher environmental regulations, ABB has carried out a number of product-recycling feasibility studies. These studies have identified potential recycling or reutilization options for insulating components that could be developed to create greater sustainability for power transmission and distribution products.

Silicone[1] rubbers and other thermosetting materials are very broadly used in electrical apparatus because of their excellent dielectric properties and robust characteristics. Huge quantities of scrap insulating components are generated both by manufacturers and utilities every year. An appropriate waste management policy should be used so that these components do not end up in landfills, but are instead recycled or reused.

Life-cycle studies show that recycling and incineration with energy recovery are the most effective ways in which to treat polymeric waste.

Recent estimates show an annual plastic product consumption for Western Europe of 40 million tons [1], from which 20 percent is thermoset. Such massive consumption of plastics inevitably results in vast quantities of waste, estimated at around 22 million tons annually, less than 40 percent of which is reutilized [1]. Polymeric wastes can be recycled, incinerated or disposed of in landfills. The results from several life-cycle studies show that recycling and incineration with energy recovery are the most effective ways in which to treat this waste. Deposition in landfills should be avoided since it implies no material or energy recovery from the waste. If the waste material is "clean" and well defined, it can be collected easily, dismantled and reprocessed for use in new products. If, however, these conditions are not fulfilled, incineration with energy recovery is probably the most suitable treatment. The advantage of using polymer wastes as fuel for power or heat generation is that most polymers have high energy content. However, it is important that the incineration is carried out under controlled conditions in plants with efficient air-pollution control devices, since polymers often contain chlorine, fluorine, bromine, sulfur or other additives, which upon combustion may result in harmful emissions. The preferred treatment of polymer wastes containing harmful organic additives is to carefully control their incineration so that these compounds are destroyed and removed. Deciding whether a product or product part should be recycled or incinerated is complex and should be considered case by case.

European waste-management directives have encouraged higher rates of recovery and recycling through the restrictive use of landfills.

In the power industry, many products contain metals embedded within the cured thermosets. These may be housed within epoxy or silicone 1. The feasibility of recovering valuable components embedded within such polymeric insulators is currently under investigation in the laboratory.

Waste management directives throughout Europe have encouraged higher rates of recovery and recycling through the restrictive use of landfills. Recent restrictions include:

Austria Additional restrictions on landfills (2004)
Denmark Ban on the deposit of combustible wastes suitable for incineration to landfills (1997)
France Ban on the disposal of non-residual wastes to landfills (2002)
Germany Ban on the disposal of non-treated wastes to landfills (1993) and combustible wastes to landfills (2001)
Netherlands Ban on all wastes that can be reused or recovered going to landfills (1995)
Sweden Ban on non-treated municipal solid wastes to landfills (1996), combustible wastes to landfills (2002), and organic wastes to landfills (2005)

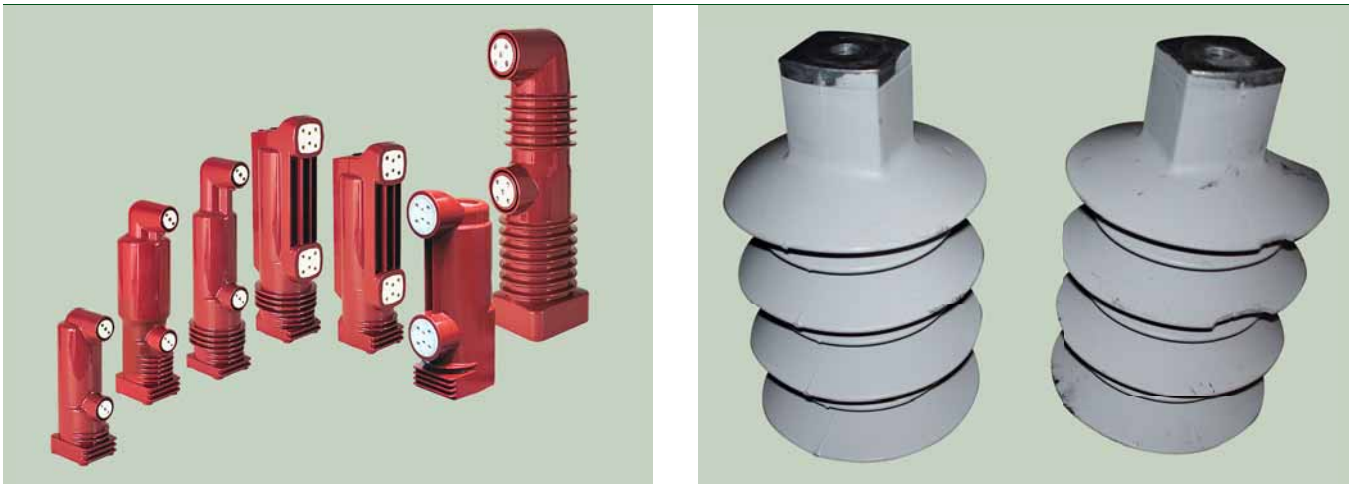
Similar new directives, eg, the directive 2002/96/EC of the European Par-

Footnotes

1) Silicones are polymers that include silicon together with carbon, hydrogen, oxygen, fillers and sometimes other chemical elements. Liquid silicone rubbers (LSR) are one type of silicones.

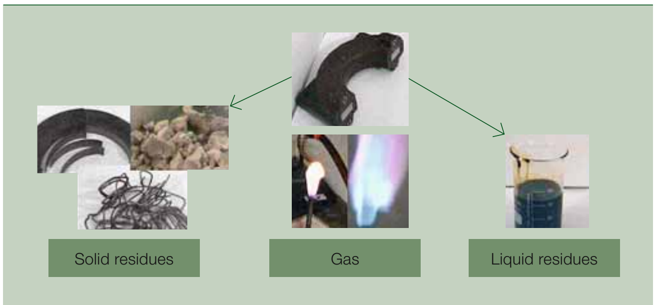
2) The "EEE" refers to equipment, which is dependent on electric currents or electromagnetic fields in order to work properly, and equipment for the generation, transfer and measurement of such currents, and fields falling under the categories set out in Annex IA and designed for use with a voltage rating not exceeding 1,000 V for alternating current and 1,500 V for direct current.

1 Thermosetting products



liament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE) states that all “electrical and electronic equipment” (EEE)[2)] should be recycled and bans the disposal of such electrical waste in landfills [2]. Greater restrictions on electrical waste, now and in the future, means that producers and final users of high-voltage apparatus should identify alternative waste-management methods.

2 Products from pyrolysis of used epoxy product



Scrap thermosets disposal methods

Cured thermosets are not classified as hazardous and can be disposed of in landfills. In fact more than 90 percent of such waste is disposed of in this way [1]. However, increasing quantities of scrap materials and a limited amount of space for their disposal has created a need for more sophisticated, sustainable technologies for the reuse of these materials.

Several different options have been proposed for the reutilization of thermosetting wastes that would avoid the use of landfills:

- Reuse in construction material
- Mechanical recycling
- Energy recovery
- Degradation

A simple way to reutilize cured epoxy-based waste is to add it to concrete or asphalt construction materials. However, since only small amounts of waste material are generated relative to the construction material required and because it is dispersed geographically over a wide area, the economic incentive to reutilize such materials in construction materials is low. Moreover, epoxy-based material is widely used to insulate electrical equipment, which means that various internal parts (cores, windings) made of metals must be removed before it can be reused. Some companies apply cryogenic techniques to recycle the embedded parts, but the quality of such parts is poor.

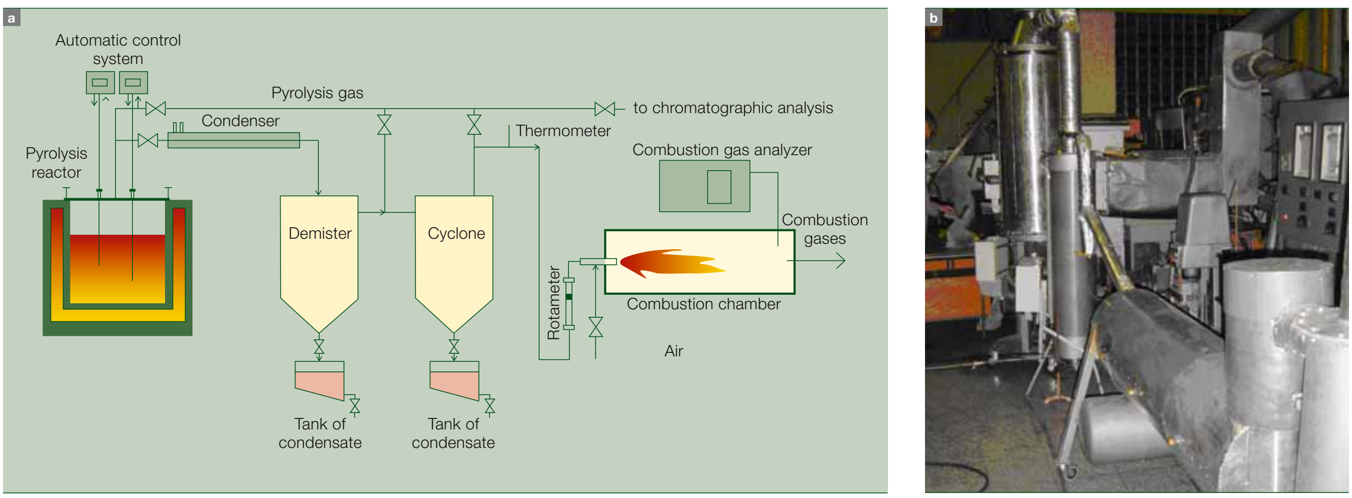
Recycling rubber materials, including liquid silicone rubbers (LSR), have so far been limited to mechanical separation methods, such as grinding. Rubbers are highly elastic, cross-linked (vulcanized) polymer materials, which, owing to their crosslinking, cannot be melted and reprocessed. This characteristic has restricted its reuse to the production of asphalt and athletic field materials; however, novel methods for devulcanizing rubbers are currently under development, which if successful, will greatly enhance the range of uses for recycled rubber materials.

Energy recovery from thermosets is an attractive alternative to recycling. Generally the energy content of thermosets is high – with lower heat values (LHVs) from 10 to 20 MJ/kg, depending on filler content – making this type of material an attractive fuel for heating and power generation. The drawback is that thermoset combustion would result in the production of large amounts of inorganic matter, in the form of filler, which would have to be disposed of economically and with minimum impact on the environment. On a positive note, air pollution from the combustion of thermosets is relatively safe; with carefully managed combustion no hazardous emissions are generated [3].

A simple way to reutilize cured epoxy-based waste is to add it to concrete or asphalt construction materials.

The degradation of plastics to lower molecular weight materials by photo-degradation, chemical-degradation or bio-degradation are also attractive options for the recycling of thermosetting polymers. Pyrolysis is a specific form of chemical degradation, which is of particular interest since it is

3 Experimental pyrolysis set-up a and pilot installation for pyrolytic thermal utilization b



attractive both environmentally and financially, and does not require the prior separation of components to recover materials and energy.

Solutions under investigation by ABB

ABB is investigating several alternative strategies by which to reutilize insulating components.

Pyrolysis

Pyrolysis is an attractive proposition for the reutilization of thermosets. It is a thermal degradation process carried out in an oxygen-free environment that results in three product categories 2:

- Pyrolytic gas
- Liquid products
- Solids (char, mineral fillers, metals)

In test experiments in the laboratory a pyrolytic reactor mainly comprised of electric heaters and a thermocouple was developed 3. The apparatus was designed so that a wide range of temperatures could be regulated within the reactor.

The gas produced by the pyrolytic thermal degradation of thermosets must be purified prior to combustion in the combustion chamber. Purification was achieved using a demister[3)] and a cyclone[4)], which condense the impurities from the gas to produce liquid products.

In the laboratory it took between three and five hours to pyrolytically degrade epoxy waste materials depending on the quantity of waste processed and the temperature at which pyrolysis was conducted. Low temperature pyrolysis was conducted at 450 °C, while high temperature processes were performed at either 750 °C or 850 °C.

4 Experimental conditions for pyrolysis at different temperatures

Process	Low temp. pyrolysis	High temp. pyrolysis	High temp. pyrolysis
Thermoset waste	1820 g	4390 g	1270 g
Pyrolysis time	3 hours	3 hours	5.5 hours
Pyrolysis temp.	450 °C	750 °C	850 °C
Products			
Gas	97 dm^3/kg resin waste	103 dm^3/kg resin waste	98 dm^3/kg resin waste
Liquid	43.96 g/kg resin waste	62.19 g/kg resin waste	226.77 g/kg resin waste
Solid	854.40 g/kg resin waste	895.22 g/kg resin waste	689.76 g/kg resin waste

Pyrolysis can be used to thermally degrade resin wastes, thereby producing gas and oil for use as fuel, while reclaiming metallic components for recycling.

In total, three different sets of experiments were performed. Optimally the organic material should be properly decomposed (ie, the goal is to reduce the carbon content of solid residues to a minimum), while retaining good quality metallic parts for recycling 4.

The results of these experiments showed that pyrolysis can be used to thermally degrade resin wastes and reclaim metallic components for recycling. The gas and oil produced by pyrolysis can be reused as fuel, recovering the energy trapped within the old discarded products.

Novel approach – cement process

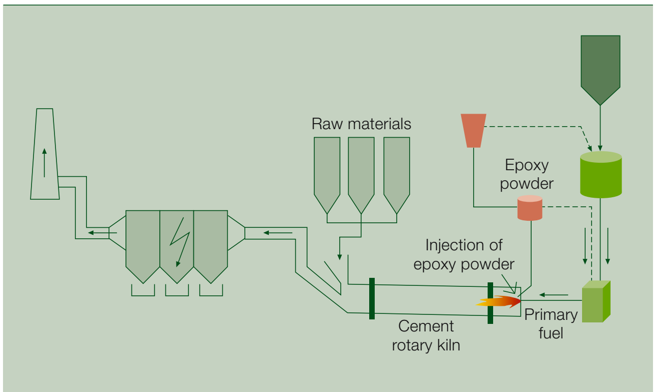
An alternative use of epoxy-based wastes is to burn them to heat the kilns of the cement industry. Due to its relatively high energy content, the epoxy can be used as an additional source of heat in a clinker burning process. Moreover, the inorganic filler (SiO_2 or Al_2O_3 in most formulations) could be incorporated into the clinker itself. Ground-cured epoxy powder would be injected into the flame (preferably in a mixture with pulverized coal) inside the cement rotary kiln 5. In the normal operation of a cement kiln, hazardous nitrogen oxides are generated. These are derived from the oxidation of chemically bound nitrogen in the fuel (fuel nitrogen oxides) and by the thermal fixation of nitrogen in the air (thermal nitrogen oxides). It is possible that such nitrogen oxides could be reduced as a result of introducing cured epoxy powder to the combusting fuel. The fuel type used affects the

Footnotes

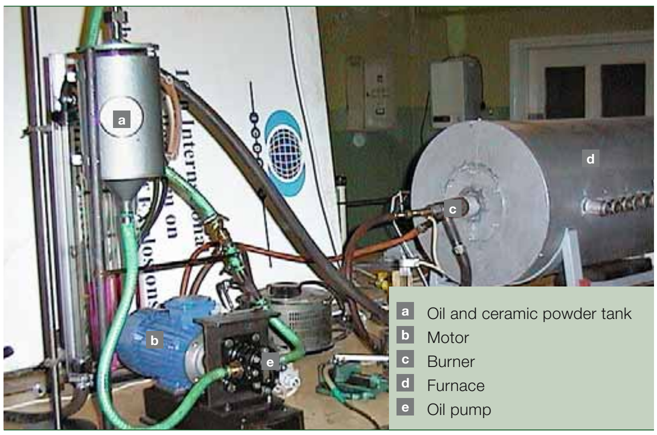
3) Demister – a device for removal of liquid droplets from a gas stream.

4) Cyclone – a device for removal of particulates from air, gas or water stream through vortex separation.

5 The concept of epoxy waste utilization in a cement rotary kiln (here the hot end of the kiln is shown)



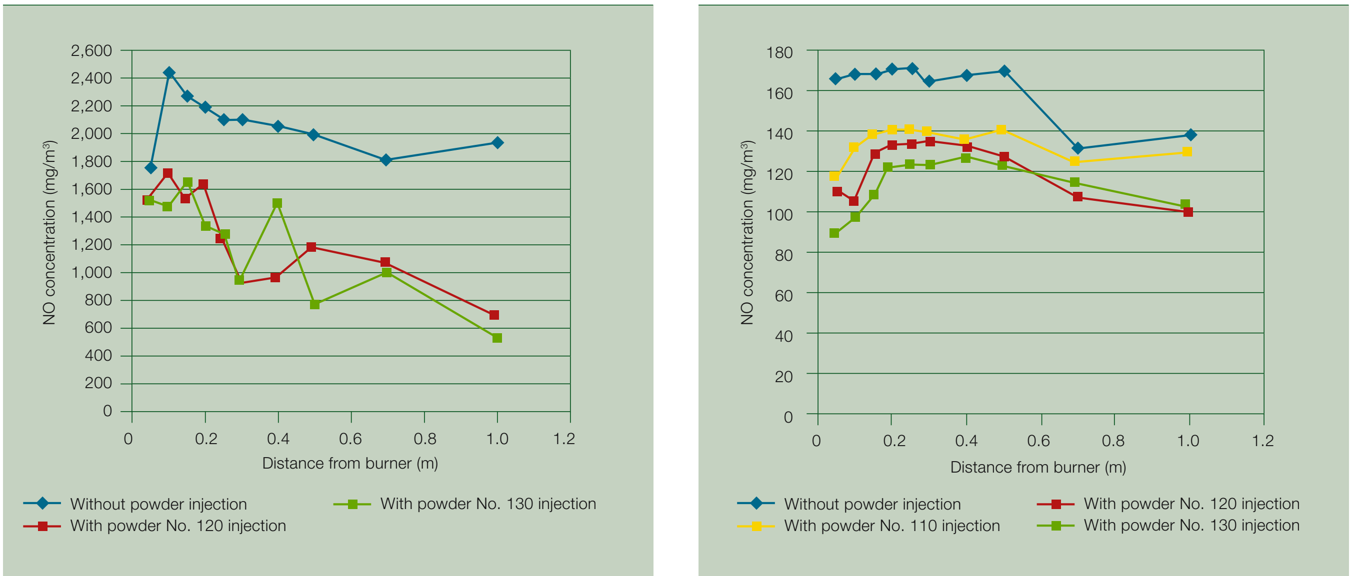
6 Experimental setup for utilization of porcelain insulators



7 NO concentration during injection of ceramic powder:

a Diesel oil supplemented with pyridine

b Natural gas



quantity and the type of NO_x generated, as does the temperature at which it burns (significant increases in nitrogen oxides are generated at temperatures above 1,400 °C). In the cement manufacturing process, the burning zone of the kiln and the burning zone of the precalciner vessel reached temperatures above 1,500 °C. These temperatures promote the formation of NO_x. The catalytic properties of introducing cured epoxy powder to the flame may promote the reduction of NO_x to nitrogen. Nitrogen oxides are the most hazardous components generated in a cement kiln creating a major environmental problem to cement manufacturers. In the wet technology[5)], emissions of NO_x can exceed 4 kg/ton of clinker [4].

This proposal for the utilization of scrap epoxy to reduce nitrogen oxide emissions is not proven, but a number of laboratory investigations on the disposal of used porcelain insulators have shown a similar utility to reduce nitrogen oxide emissions [5]. Laboratory tests have shown that diesel oil mixed with a ceramic powder, obtained by grinding used porcelain insulators, can reduce nitrogen oxide emissions when supplied to the burner.

To increase the amount of nitrogen oxides generated in the process experimentally, up to 10 percent weight per volume pyridine C_5H_5N was added to the diesel oil. This allowed nitrogen oxide concentrations in the flue gases to exceed 2,000 mg/m³. Such concentrations made it easier to record the effects of adding ceramic powder to the diesel oil on the concentration of nitrogen oxides produced. To check the effect of the process on thermal nitrogen oxides, additional tests were carried out using the same laboratory equipment, but replacing the diesel oil with natural gas as fuel. In this case, the oil burner was removed and a natural gas burner (6 kW thermal capacity) with the powder injection system was installed 6. All NO concentrations were recalculated for a 3 percent oxygen level in order to compare the results of the combustion tests with and without the powder injection.

The introduction of the ceramic powder results in a significant reduction of nitrogen oxides formed during combustion of diesel oil and natural gas.

The results show that the introduction of the ceramic powder resulted in a significant reduction of nitrogen oxides formed during combustion of both types of fuel. The magnitude of the reduction of the respective NO_x concentrations is presented in 7. The concentrations of NO_x in 7a are one order of magnitude greater than those in 7b, because the former, in addition to the thermal nitrogen oxides, also includes the fuel nitrogen oxides resulting from the addition of pyridine. It is interesting to note that the magnitude of the reduction in NO_x concentration in 8a increases with the distance from the burner, while the opposite trend is observed in 8b. This is an effect of various temperature distribution profiles for both fuels and the resulting different mechanism of nitrogen oxide formation in the flame region along the combustion chamber. Regardless of these trends, 7 and 8 suggest that the addition of ceramic powder to both diesel oil and natural gas fuels can help reduce NO_x emissions during combustion.

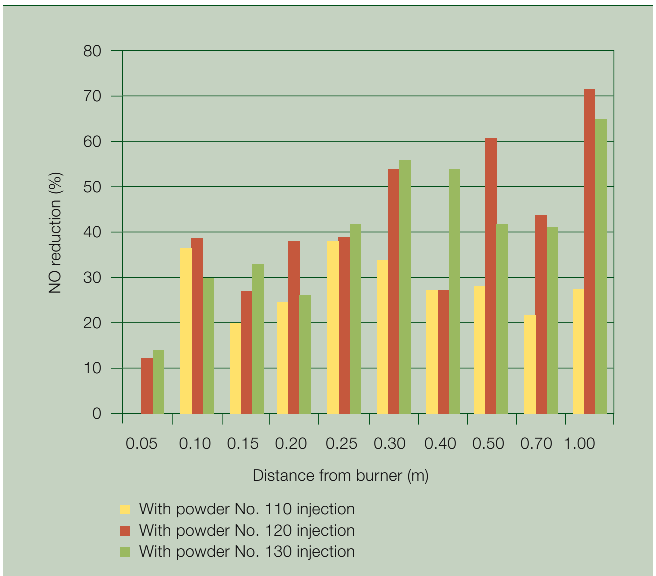
The observed reductions in NO_x emissions can be explained on the basis of

Footnote

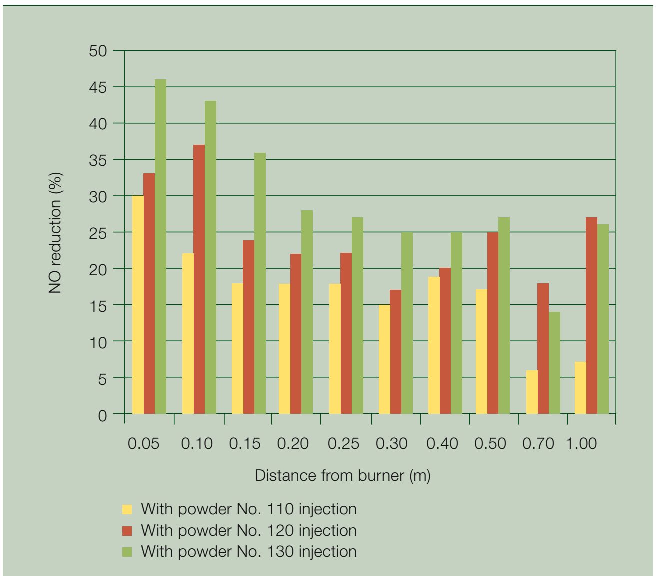
5) Cement production is either "wet" or "dry," depending on the water content of the raw materials used. The wet technology processes slurries instead of dry powders. Although the chemistry is easier to control, it requires much more energy to drive off the water by evaporation from the slurry. The dry technology is far less energy intensive.

8 Reduction of NO concentration during injection of ceramic powder:

a Diesel oil supplemented with pyridine



b Natural gas



some catalytic effect of the ceramic powder components 8. This is probably the same effect as was observed by DeSoete [6], who pointed out that NO can be destroyed in the presence of a reducing agent (eg, CO) on both cenospheres[6] and even on the wall of an empty quartz reactor. DeSoete proposed reaction kinetics models for the destruction of NO and HCN on fly ash, gas phase formed soot, and cenospheric soot. In all cases, the nitrogenous species was efficiently destroyed. The components found in ceramic insulators are similar to the components found in fly ash, suggesting a similar mechanism for the promotion of NO reduction using ceramic powder. However, at present, the influence of metal oxide concentrations on the reaction kinetics of NO and CO reduction at the ceramic powder surface is not well understood. A similar positive effect on the reduction of NO_x emissions is expected for an epoxy powder containing mineral fillers. It is important to note that Fe_2O_3, which is commonly used as a dye in epoxy mixtures, is known for its strong catalytic effect.

ABB has identified potential recycling and reutilization options for insulating components.

Scrap surge arresters

Recently, silicone-housed surge arresters have found a broad application in a wide range of medium- and high-voltage systems. A polymer surge arrester consists of polymer housing with metallic flanges and terminals made of aluminum, steel or copper (metal oxide varistor[7] blocks are the most important components in surge arresters).

ABB aims to create greater sustainability for power transmission and distribution products.

The metal-oxide varistors are sintered[8] bodies composed of mainly ZnO (90 percent) and other oxides, mostly of heavy metals. Since this type of silicone rubber material is rel-

9 Recycled components from scrap surge arresters

a

b

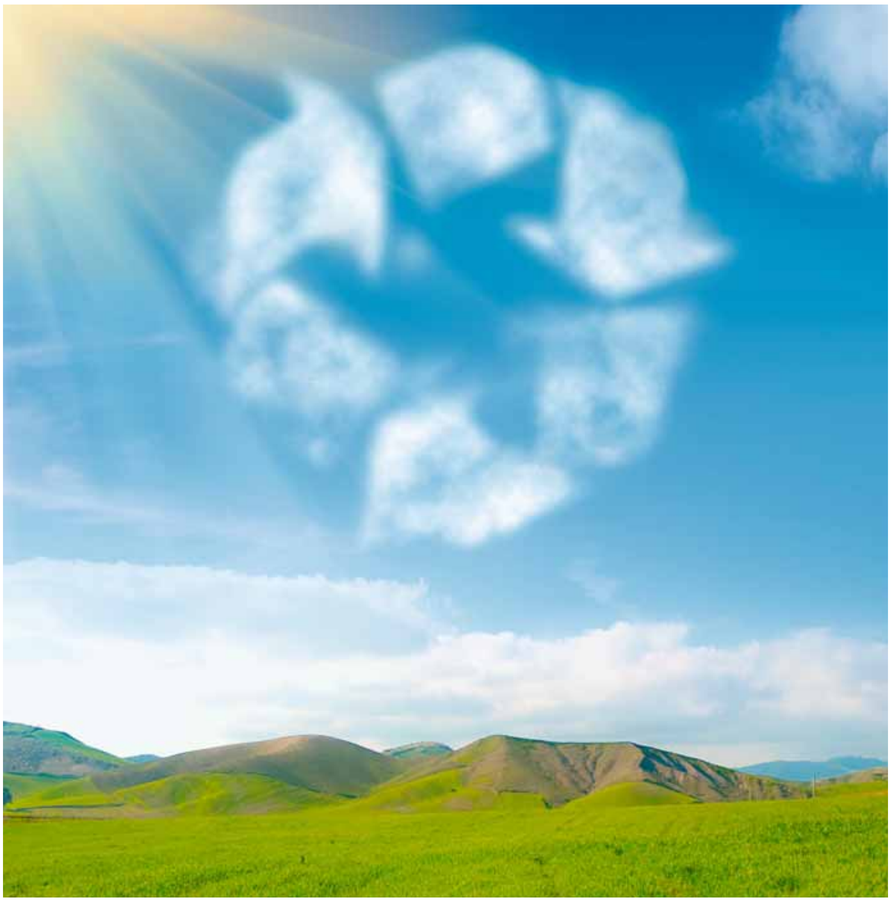
Footnotes

6) A cenosphere is a lightweight, inert, hollow sphere filled with inert air or gas, typically produced as a byproduct of coal combustion.

7) Varistor – a type of resistor with significantly non-linear current-voltage characteristics.

8) Sintering is a method for making objects from powder, by heating the material below its melting point until its particles adhere to each other.

10 Products after wrong recycling procedure



atively new, there is no commercial method for the efficient recycling of used surge arresters.

ABB has patented techniques to reutilize thermoset components.

Investigations have been made for possible ways in which to recycle LSR insulation. Decomposition methods for silicone rubber materials are limited. The most common disposal method is combustion (incineration). However, combustion of silicone rubbers is associated with temperatures in excess of 900 °C, which may result in the emission of the heavy metals. The silicone rubber itself has a relatively high combustion heat (17,000 kJ/kg) in a range not so far off that of hard coal (ranging from 25,000 to 30,000 kJ/kg).

Considering all recycling criteria, laboratory tests were performed using the pyrolysis process to thermally degrade the silicone. The same experimental setup used for the epoxy waste was employed. Different temperatures were tested to optimize the process parameters so that good quality internal parts (mostly zinc oxide varistors and other metallic parts) could be recovered for recycling 9. Under non-optimized conditions components were destroyed and could not be reused for any application 10. It should be noted that at this stage in the study no detailed investigations were done to determine the electrical performance of the recycled varistor blocks and their potential reuse.

Long-term perspectives

Investigations made by ABB in laboratory experiments confirm the availability of technologies for reutilizing (recycling) different types of thermoset components. These techniques have been patented by ABB and provide an opportunity for their commercialization. However, to succeed in this endeavor, an appropriate policy regarding the efficient collection of scrap components should be initiated by waste disposal organizations with the strong support of local governments. This will ultimately result in lower quantities of thermoset waste ending up in landfills and a higher proportion of valuable component recovery for reuse by manufacturers.

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References

[1] Association of Plastic Manufacturers in Europe (2004). An analysis of plastics consumption and recovery in Europe 2002-2003, Brussels.
[2] Directive 2002/96/EC on WEEE of the European Parliament (2003), Brussels.
[3] **Pickering, S.J., Benson, M.** (1991). The recycling of thermosetting plastics in Plastic Recycling Meeting, London.
[4] European Environment Agency (1996). Atmospheric Emission Inventory Guidebook, Copenhagen.
[5] **Sekula, R., Wnek, M., Slupek, S.** (1999). Potential utilization method for scrap ceramic insulators. *Journal of Solid Waste Technology and Management, 26 (2).*
[6] **DeSoete, G.G.** (1980). Heterogeneous nitric oxide reduction on flame borne solid particles. *Proceedings of Sixth Members Conference*. IFRF, Noordwijkerhout.

Optimal trade-offs

Achieving energy efficiency and environmental compliance is not a problem thanks to advanced process control

Konrad S. Stadler, Eduardo Gallestey, Jan Poland, Greg Cairns

Modern industry works hard to achieve efficient production. However, this can often be quite difficult because many companies are bound by complex contractual and environmental conditions. This in turn increases the complexity of operations for both the operators driving the process and the plant managers setting the production goals, requiring them to make trade-offs between the amount and type of production, the availability of energy and the volatility of its costs.

Process industries can now virtually "be all things to all market conditions." With ABB's product cpmPlus Expert Optimizer, customers have all the automatic control tools needed to stabilize and control a process to effectively manage the complexity arising from new market conditions. Moreover, state-of-the-art mathematical algorithms have been packaged to easily tackle the optimization and control problems that were intractable just a few years ago.

Sustainable processes

With ever-changing market conditions, companies cannot afford to sit back and survive from the rewards of past successes. Indeed, according to Akira Mori, one of Japan's most successful businessmen, "Past success stories are generally not applicable to new situations. We must continually reinvent ourselves, responding to changing times with innovative new business models." As well as business models, innovative products, processes and services are necessary if companies and their customers are to survive what can only be called truly testing times. Rather than waiting for change to come, companies should be looking for changes in the market that may be a developing trend. Determining early enough if this trend is likely to impact the long-term success of a business enables the best solution to be found.

For some time, successful engineering teams at ABB have been using optimization techniques on a daily basis to serve its customers. In anticipation of changing market conditions and of customers' future need to meet these changes, ABB created a comprehensive engineering tool known as cpmPlus Expert Optimizer. Featuring all modern control techniques, Expert Optimizer facilitates the speedy deployment of controllers to satisfy demanding project criteria.

cpmPlus Expert Optimizer uses available measurements to initiate automatic adjustments to plant actuators to increase efficiency at a given quality. As well as increasing process efficiency, cost effectiveness and reliability are also improved. Similar to an autopilot in an airplane, Expert Optimizer achieves results by ensuring that the best possible actions are applied accurately, tirelessly and consistently at all times. In addition, its implementation follows stringent standardization procedures to ensure a high level of success and long-term maintainability. cpmPlus Expert Optimizer has a successful track record in the marketplace with more than 300 reference sites worldwide.

This software tool has the following characteristics:

- It combines optimal production scheduling techniques with those of classical advanced process control and artificial intelligence.
- It is flexible enough to handle applications in different industries with different requirements.
- It is user friendly in that the complexity is placed out of sight, thereby allowing its usage by non-specialists.
- It reduces deployment time via modularity, reusability and scalability.

Expertly using process knowledge

One of the strengths of ABB's cpmPlus Expert Optimizer is that it can use fuzzy logic and neuro-fuzzy tools to develop applications. Fuzzy logic inference systems incorporate human knowledge to make and implement effective decisions during a process, while neuro-fuzzy networks are used to learn relationships between key process variables. The integration of these complementary control techniques, coupled with ABB's and the customer's extensive process experience and expertise, allows the engineering of powerful robust solutions, which provide substantial financial benefits to the factory for extended periods of time.

cpmPlus Expert Optimizer achieves results by ensuring that the best possible actions are applied accurately, tirelessly and consistently at all times to increase process efficiency, cost effectiveness and reliability.

A Model Predictive Control expert

In addition to the classical tools of artificial intelligence, cpmPlus Expert Optimizer boasts a mature model predictive control (MPC) toolbox.

How does MPC work? Based on the predictive capabilities of a mathematical model, a sequence of future optimal control actions is derived[1]. The first term of the sequence is applied to the plant. When measurements (or new information) become available, a new sequence is determined. Each sequence is computed by means of an optimization procedure, which follows two goals:

- Optimize the performance
- Protect the system from constraint violations

Expert Optimizer allows for linear, nonlinear and hybrid models with continuous and Boolean variables. This is a remarkable feature. Indeed, while linear mathematical models are well established to control industrial processes, nonlinear and hybrid models (ie, models with mixed continuous and binary states) are only now being applied to processes in which ABB customers are interested.

MPC not only requires the development of a mathematical model to describe the process, but it also requires the selection – or design – of a suitable cost-revenue index (otherwise known as a cost function), which takes into account the goals that must be achieved. Depending on its design, the function could penalize deviations from given operating points or it can simply represent operating costs. The optimal inputs to the system are calculated through minimization of this function within the constraints defined by the process model. To be successful the minimization algorithms must exploit the structure of the problem as described by the model type (linear, nonlinear, hybrid, etc) and the optimization function characteristics.

In Expert Optimizer the same MPC framework is used to perform three complementary tasks important for advanced process control:

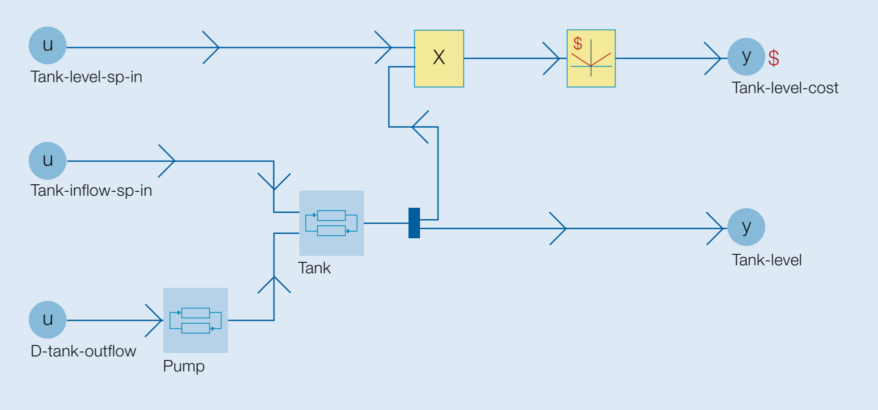
State estimation This task implements the so-called moving horizon estimation (MHE). The MHE considers the most recent past (the horizon over which the measurements are considered) to estimate the current states of the model as the initial conditions that minimize a trade-off (cost function) between sensor and process noise. This method can be exploited for parameter estimation using the augmented state approach.

Process simulation Using a given initial condition for the model states, this task simulates the model to give a future view while the manipulated variables are kept at their current values. The end result is a representation of the systems open-loop behavior at current conditions.

Process optimization With a given initial condition for the model states and a cost function, this mode calculates the optimal values for the manipulated variables that minimize the cost function over a receding horizon. The associated trajectories for manipulated variables, model states and model outputs (controlled variables) then become available for display and further post-processing.

1 The Expert Optimizer library for generic mixed logical dynamical (MLD) blocks

2 A simple tank-pump system is modeled in Expert Optimizer



Scheduling by means of MLD systems

The model-based environment of the new Expert Optimizer has adopted the mixed logical dynamical (MLD) modeling class [1]. MLD systems, developed at the Automatic Control Laboratory at the Swiss Federal Institute of Technology[2] (ETH) in Zürich, generalize a wide set of models, in particular those that exhibit both continuous and discrete behavior, ie, models that describe a hybrid system. The ability to model hybrid systems significantly increases the range of applicability of ABB's Expert Optimizer. This is because unlike linear models, MLD systems are able to model constraints such as logic relationships of the type "if unit 1 ON then unit 2 OFF"; or production constraints "either NO production, or production between MIN and MAX."

One of the strengths of ABB's cpmPlus Expert Optimizer is that it can use fuzzy logic and neuro-fuzzy tools to develop applications.

With MLD systems, the optimization task is transformed into a mixed-integer linear or quadratic problem for which computationally efficient solvers exist. Depending on the needs, the same framework can be applied either as an open-loop, decision-making (scheduling) tool or as a closed-loop, disturbance-rejection (rescheduling) tool [2].

In short, the key advantages of using the combined MLD/MPC approach include modeling flexibility and acceptable computational requirements.

Build the model graphically

One of the goals of Expert Optimizer is to make the MPC methodology accessible to non-specialists. There is a drawback with the MPC approach and that is the need to create a process

Footnotes

[1] A typical scope is the short- to medium-term evolution of the system.

[2] ABB launched a strategic collaboration with ETH about nine years ago.

model with sufficient accuracy. To overcome this, ABB proposes breaking the process into smaller but sound components. For example, a hydroelectric power plant could be split into the reservoir, dam, turbine, generator and grid. The idea is to model each part independently of the others and to represent it graphically with a block. Each graphical block stores its own constraints and dynamics, and its input and output (I/O) ports match the inputs and outputs of the mathematical model. The complete process model is then obtained by graphically connecting the I/O ports of the various blocks. The cost function that defines the optimal control problem is also represented as a graphical block. If, for example, the goal in the hydroelectric plant is to maximize profits made from the sale of electricity, the output of the generator block – representing the power produced – should be linked to the cost function block where the time-varying electricity tariffs would be stored.

The modularity of the approach simplifies the modeling phase and makes it easier to engineer, modify and maintain the models. Furthermore, it allows the creation of libraries containing standard blocks that can be reused in different processes simply by dragging and dropping them.

An example of the Expert Optimizer library for generic MLD blocks is shown in 1. Included in this library are basic elements, such as I/O variables, process delays, gains, state-space models, summations of MLD variables, and soft and hard constraints. Similar libraries exist for modeling the logic part of a hybrid system. In general, any process can be modeled by simply connecting these MLD blocks together, as illustrated by the simple tank-pump system in 2. The cost functions are created using the same building blocks of piecewise linear operations. The user may, of course, import his own MLD models (for example, those originating from black box identification algorithms) into Expert Optimizer. In fact, Expert Optimizer 6.1 offers a full-blown model identification tool.

The ability to model hybrid systems significantly increases the range of applicability of ABB's Expert Optimizer.

Expert Optimizer at work

Several projects implementing Expert Optimizer's new model-based optimization capabilities have been installed and are running successfully in different domains. The most significant examples are in:

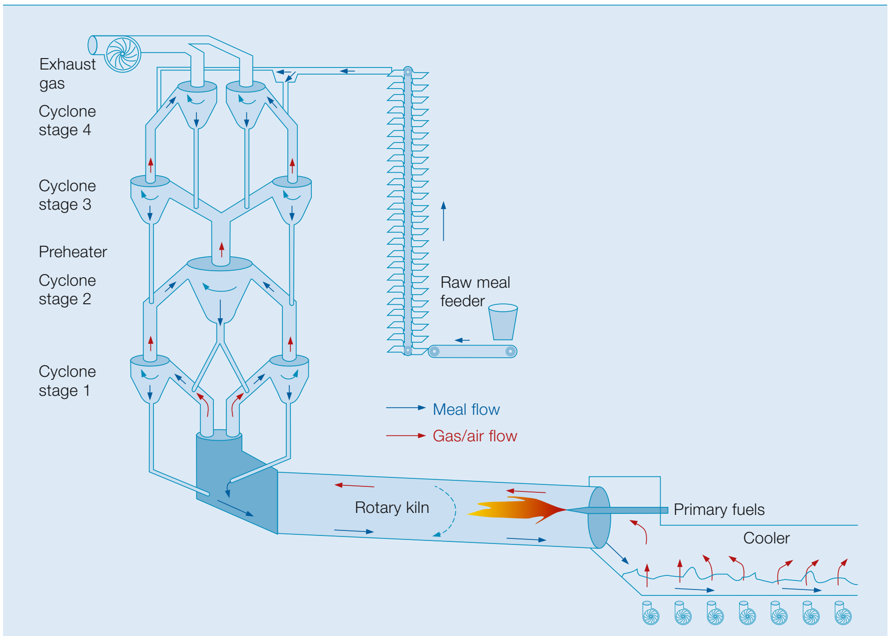
- Closed-loop process control, ie, cement mill control, blending optimization and precalciner control [3]
- Production planning and scheduling, ie, cement mills scheduling [4], titanium dioxide production scheduling and water distribution
- Economic process optimization, ie, alternative fuels management
- Thermal power plant optimization [5]

Kiln control

A standard application for Expert Optimizer is kiln control in the cement clinker production process. A cement clinker production unit is shown in 3. The clinker minerals are formed at about 1,400 °C within the rotary kiln. This process requires a lot of thermal energy, which is provided by fossil fuels and to a substantial degree by alternative fuels (tires, plastic, etc). To make the process more energy efficient the hot exhaust gas travels further up the kiln and into the preheater tower. The raw meal travels in the opposite direction and picks up energy from the gas on its way down through the preheater tower and into the rotary kiln. As it heats up, the meal undergoes chemical reactions, such as calcining, which pre-treat it before it enters the mineral-forming phase in the last third of the rotary kiln. A cooler forces ambient air through the clinker bed, thereby guaranteeing efficient heat exchange and rapid cooling of the clinker. This in turn ensures that the formed minerals remain in their required form.

The clinker production process is highly interconnected in that changing one of the main actuators (raw meal feed rate, exhaust gas flow rate, fuel input, rotary kiln speed) affects all the main process indicators (burning zone temperature, cyclone stage-two temperature, oxygen level in the kiln). Moreover, stabilization of the process depends strongly on the composition of raw meal as the energy requirements at various phases of the process are influenced by the different meal components. To reduce the amount spent on fossil fuels, up to 70 percent of the fuels used (depending on the process configuration) are alternative, such as waste. This in turn introduces

3 Cement clinker production unit: Gas flow is indicated with the red arrows and meal flow with the blue arrows



highly variable heat input from the fuel combustion. It is therefore important to know how the reaction conditions in each phase of the process are affected. The quality of the clinker depends on it. In other words, if the system cannot compensate on time as the cold meal travels along it the chemical reactions needed to form clinker cannot take place.

Expert Optimizer makes the MPC methodology accessible to non-specialists by breaking the process into smaller but sound components, which are modeled independently of each other.

The process is therefore divided into compartments or zones, with each zone influencing the one beside it. This allows predictions to be made regarding the evolution of the energy within a zone and therefore on the temperature profile along the whole production process. Until recently a fuzzy-logic-based controller was used, but this has now been replaced by the model-based MPC approach.

Predicting the feed (blue) and gas (red) temperature profiles, as shown in 4, provides valuable information when it comes to stabilizing the process to ensure the desired clinker quality and production rate. The problem is the temperature profiles have to be derived from a restricted number of measurements taken at a few points along the process (dark blue dots in 4). To overcome this limitation, MHE is used. By reformulating the optimization problem to look backwards in time rather than forwards – as in MPC – an accurate temperature profile can be estimated. This estimation enables for the MPC algorithm to derive the best sequence to change the manipulated variables such that the process targets are optimally reached.

The controller performance is shown in 5 where the temperature of the sintering zone (BZT) is kept close to its target while at the same time maintaining the temperature in the preheater tower (BET) to within a close range. The trade-off between maximizing the production (FEED) and keeping the critical process variables within acceptable ranges can easily be seen. Typically, the controller adjusts the fuel input (ENERGY). However, whenever the process temperatures indicate that the system will rapidly cool down, the controller reduces the feed rate (FEED) to support a faster recovery.

Pulp and paper plant scheduling

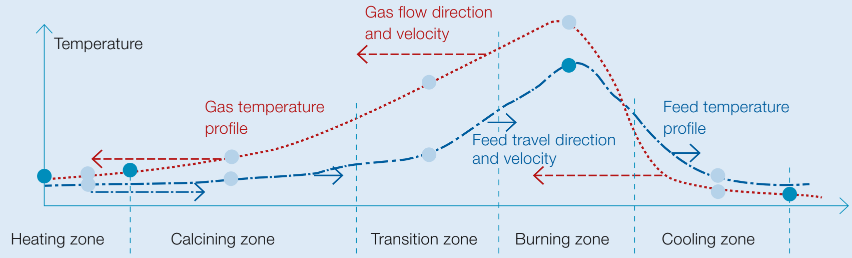
Pulp and paper plants are ideal environments in which to demonstrate the power of nonlinear MPC and Expert Optimizer. The process used in these plants is challenging in that the right mix of chemical additives must be applied at the right moment and under the right conditions in order to meet stringent quality requirements.

ABB's nonlinear MPC schema allows a mill to be better utilized by continuously monitoring its current state and giving decision support in real time, aiming for maximum profit at minimal cost. The tool optimizes mill operations by balancing supply and demand between subsystems. Every subsystem or buffer has to be fed material and sufficient supply must be available for the subsystem to produce as required.

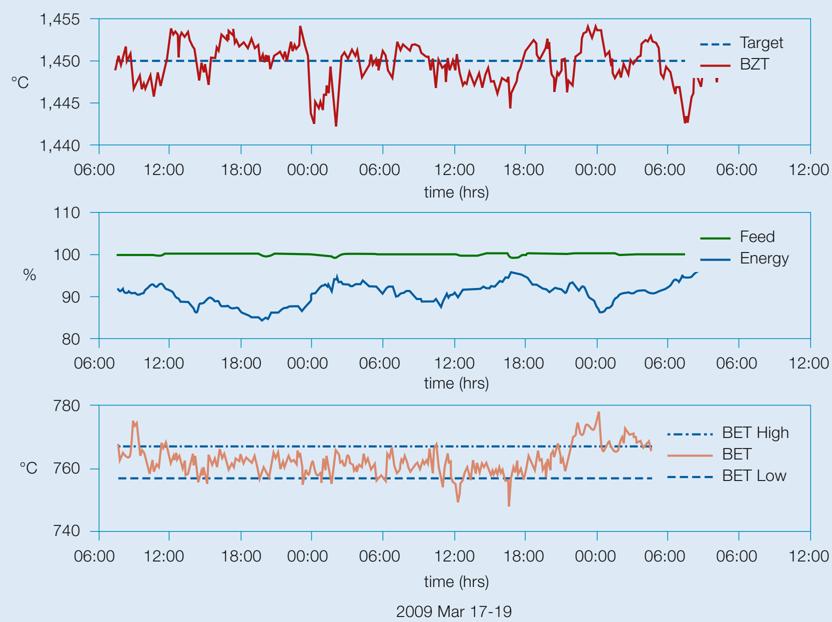
The relationships become nonlinear because they must cover a large oper-

4 Temperature profile for feed (meal) and gas (air) with the main characteristic zones of the clinker production process

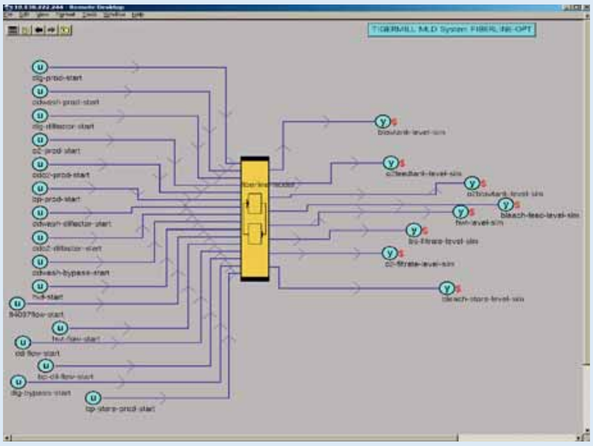
The corresponding arrows provide qualitative information about the gas and feed flow direction, and velocity. The dark and light blue dots respectively indicate where the temperature can be measured or where it needs to be estimated.



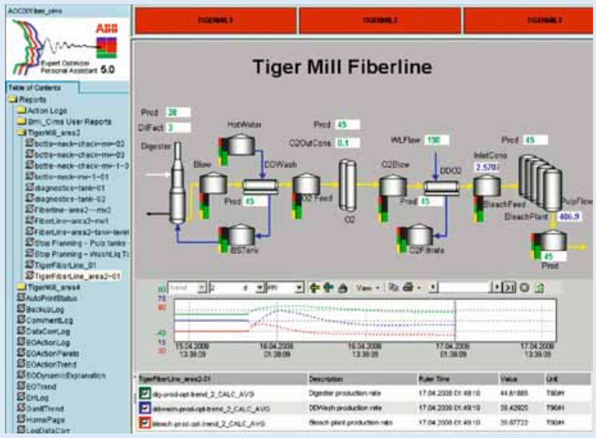
5 Performance of an MPC kiln controller



6 A Modelica model inside the Expert Optimizer run-time tool



7 A typical Expert Optimizer operator interface



ating range of plant set-points. In many cases proper scheduling necessitates a variety of models to describe, for example, the sodium and sulfur chemistry as well as the fiber balance. Very often more detailed models for fiber lines are developed to describe, for instance, kappa number and brightness 6.

The development of cpmPlus Expert Optimizer is the result of a fruitful and long-term collaboration between ABB's business units and corporate research.

With ABB's nonlinear MPC schema, customers can typically expect the following functionality:

- Online production planning
- A stop planning tool (stops and limits capacity at certain process sections)
- Soft sensor functionality
- Diagnostics for measurement points
- Bottleneck analysis

Using the nonlinear models and real-time data from the plant floor, as well as taking into consideration events such as the maintenance of key equipment, Expert Optimizer produces predictions of all key variables, which are valid for several days. Typically, these models are large, consisting of dozens, if not hundreds, of dynamic states, and manipulated and controlled variables. In addition, they are tailored to predict the process variables that cannot be measured directly.

These "control applications" are related more to economic process optimization rather than to regulator control. In other words, they try to exploit degrees of freedom in order to increase the plant financial performance.

A model partnership

Twenty years of experience in the process industry and knowledge of established control techniques like fuzzy logic, rule-based control and neuro-fuzzy tools have been combined to create sophisticated state-of-the-art model-based optimization techniques.

Complex real-world applications in the areas of closed-loop process control, open-loop decision support, as well as advanced production planning and scheduling, and economic optimization can now be tackled by a single product. Modeling, optimization and simulation capabilities are easily accessible through the Expert Optimizer graphical interface 7. Flexibility is ensured by a modular structure and by providing libraries of reusable components.

The development of cpmPlus Expert Optimizer 6.1 is the result of a fruitful and long-term collaboration between ABB's business units and corporate research. In fact this collaboration serves to illustrate the benefits that come about when industrial needs are met with the achievements of long-term research.

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References

[1] **Bemporad, A., Morari, M.** (1999). Control of systems integrating logic, dynamics, and constraints. *Automatica 35*(3), 407–427.

[2] **Gallestey, E., Stothert, Castagnoli, D., Ferrari-Trecate, G., Morari, M.** (2002). Using model predictive control and hybrid systems for optimal scheduling of industrial processes. *Automatisierungstechnik 6*, 285–293.

[3] **Stadler, K. S., Wolf, B. and Gallestey, E.** (2007). Precalciner control in the cement production using MPC. *Proceedings of the 12th IFAC Symposium on Automation in Mining, Mineral and Metal Processing*, 201–206.

[4] **Castagnoli, D., Gallestey, E., Frei, C.** (2003). Cement mills optimal (re)scheduling via MPC and MLD systems. *Proceedings*, ADHS 03, 82–87.

[5] **Ferrari-Trecate, G., Gallestey, E., Letizia, P., et al.** (2004). Modeling and control of co-generation power plants: A hybrid system approach. *IEEE Trans. Contr. Syst. Tech.*, *12*(5), 694–705.

Greening the gate model

Making products sustainable by design

Lennart Swanstrom

Many of ABB's technologies are, by nature, environmentally friendly. Electricity is probably one of the cleanest and most efficient ways of transmitting energy. Environmental benefits can also be identified for many other ABB products: Process-control systems, for example, help reduce wastefulness in manufacturing. Over the years, these technologies have been improved and developed to further increase their efficiency. This was mostly motivated by the will to improve productivity by reducing losses – ecological gains were often a byproduct of economic improvements.

The rise of environmental awareness has changed this paradigm. Processes and products are now optimized to be both economic and green. This article takes a look at how ABB is developing greener products by taking sustainability into account in the design phase.

For ABB, the continuous search for ways of minimizing the environmental footprint of its products and activities has become a core focus. It is now a vital consideration in all aspects of the company's activities. ABB recognizes that awareness of the topic must be present from the boardroom to the factory floor. To achieve this target, the company has adopted a set of sustainability management goals including (among others):
- Integrating sustainability aspects into decision-making processes on all management levels
- Raising the awareness and commitment of every employee

ABB's overall environmental strategy further includes audits and reviews of its manufacturing processes, and the

Sustainable processes

implementation of sustainability management systems on individual manufacturing and servicing sites. Besides the strictly environmental aspects that these measures include, they focus on such topics as health and safety management.

Raising issues and reviewing and discussing topics does help to keep them in people's minds and influences decisions. However, to repeatably and continuously deliver the required results, verifiable steps must be anchored in process definitions. Fortunately, any properly managed process already has such a definition. Without such a definition, any process would be difficult to manage and risk escalating out of control or exceeding time and budget constraints. Quality management would be almost impossible. The definition is therefore already in existence, and the challenge is to modify or extend this definition to include sustainability-related measures.

> When new processes are introduced there is sometimes a risk that, in practice, they are bypassed because they are too challenging to implement and not supported by the workforce.

When it comes to product development in any part of the ABB Group, the company has already for some time been using a process definition it calls the ABB Gate Model Factbox.

The goal was thus to modify the gate model by adding sustainability criteria. These measures included:

- Environmental checklist (eg, hazardous materials, energy efficiency and recyclability)
- Support tools

One important goal was to assure the extended gate model was adopted and applied across the company. A prerequisite to this was that it could be understood by all those who needed to apply it. When new processes are introduced there is sometimes a risk that, in practice, they are bypassed because they are too challenging to implement and not supported by the workforce. In designing the sustainability version of the ABB Gate Model, great care was taken to assure that all demands were feasible. The individual development units should be able to apply the plan without any need for supervision.

To enable this, a sustainability toolbox was designed and made available on the company's intranet. This toolbox lists all aspects needing to be considered. These include:

- Energy efficiency and CO_2
- Materials selection
- Restricted substances
- Life-cycle assessment
- Environmental and climate declarations
- Supplier qualification

The product development process must specifically refer to the following points:

1) ABB's list of prohibited and restricted substances
2) Environmental and health & safety legislation
3) Possibilities to reduce energy consumption during product use
4) Risks during manufacture and/or operation of the product
5) Recycling and end-of-life issues

> These sustainability aspects are now mandatory across the entire ABB Group.

This checklist is referred to at gate 1 of the ABB Gate Model and again at gates 2 and 4. In the latter gates, a check is furthermore required to ascertain that the identified problems have been acted upon, and that the requirements are still valid.

These sustainability aspects are now mandatory across the entire ABB Group, and all new products now being introduced have been developed using this methodology.

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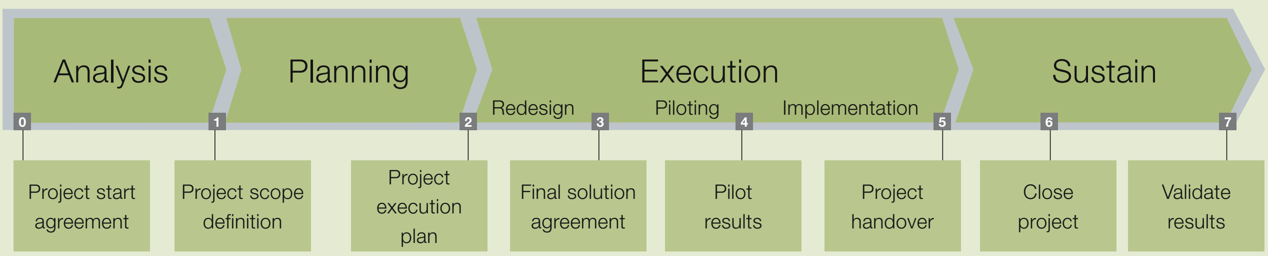
Factbox The ABB Gate Model

The gate model is a description of a development process that is mapped as a timeline. This line is separated into sections divided by gates. The gates mark important milestones, and the process cannot pass one of these gates and proceed into the next phase without a formal decision. Such a decision is based on an assessment of the project status. All project aspects that are relevant at that stage are examined and future actions decided. ABB has defined a specific version of the gate model. This ABB Gate Model is now used in all development processes within the company. It permits an orderly, controllable and accountable development activity.



A worthwhile investment

The drive to reduce emissions and energy consumption

Jukka Tolvanen, Timo Miettinen

Variable-speed drives (VSDs) control the speed of machinery, pumps, mixers, fans and compressors to match the needs of the process. In many applications VSDs save so much energy that their economic payback time is only a matter of months. A new approach to the assessment of environmental impacts shows that the environmental payback time of VSDs can be even shorter, in many cases as little as one to two days.

Sustainable processes

AC variable-speed drives (VSDs) operate by converting the fixed supply from the network to a variable voltage and frequency in response to an electrical control signal. The change in frequency results in a corresponding change in the speed (and torque) of the motor coupled to the drive. This means that the motor speed, and therefore the speed of the equipment being driven, can be set on the basis of external parameters, such as flow rate or temperature.

Speed control can significantly boost the efficiency of the entire motor driven system. In the case of conventional systems such as pump and fan applications, for example, the electric motor drives the pump or fan at full speed and then the desired flow rate of liquid or gas is achieved by restricting the output by means of valves, vanes or similar "throttling" devices.

Running the system at full speed and then restricting the output is obviously very inefficient. Some applications have proven that even a modest decrease in motor speed will considerably reduce energy consumption. According to the affinity laws, which govern the performance of pumps and fans, a pump running at 80 percent speed, for example, uses only 64 percent of the energy and slightly more than 50 percent of the power than one running at full speed.

There is a huge scope for energy and emissions savings through speed control by VSDs. Pumps, fans, compressors, extruders and other motor-driven applications account for two-thirds of industrial electricity consumption, which in turn represents 40 percent of the overall electricity use in the world. However, less than 10 percent of motors are operated by drives and, of motor-driven applications under 2.2 kW, as many as 97 percent have no form of speed control at all! In Europe it has been estimated that if VSDs were used in motor-driven systems throughout the continent, annual savings in electricity consumption totaling 50 million MWh could be achieved. This is equivalent to 25 million tons of carbon dioxide[1], or roughly a quarter of the total annual emissions of Finland.

Variable-speed drives offer the most effective method of controlling a motor's speed, thereby contributing significantly to energy saving.

Payback time

The economic benefits of VSDs are relatively easy to calculate, as the investment cost, reduction in energy consumption and cost of power are known. This in turn enables the payback time to be readily computed. Quantifying the environmental effects of VSDs, however, is somewhat more complicated.

The methodology generally used to study the environmental impacts of manufacturing, use and disposal of products is life-cycle assessment (LCA). ABB conducts LCA work in accordance with the requirements of the ISO 14000 series of environmental management standards. LCAs are designed to cover all the phases of a product's life cycle: from the production of raw materials and components to its disposal. Data is collected on all the relevant inputs and outputs, and this is then related to environmental impact categories such as global warming and ozone depletion. The selection of impact categories depends on the purpose of the LCA, and the ones most commonly considered for VSDs are shown in 1. The areas of highest impact are identified, and then addressed in order to reduce the overall environmental burden.
In this way, LCA studies highlight the importance of Design for the Environ-

1 Common categories of environmental impacts evaluated during life-cycle assessment (LCA) studies

Category of impact		Description
Global warming potential	GWP	Translates the quantity of gases emitted into a common measure to compare their contributions (relative to carbon dioxide) to the absorption of infrared radiation from the Earth over a 100 year perspective
Acidification potential	AP	Translates the quantity of sulfur dioxide and nitrogen oxides emitted into a common measure to compare their contributions to the capacity to release hydrogen ions
Eutrophication potential	EP	Translates the quantity of nutrients (mainly nitrogen and phosphorus) emitted into a common measure expressed as the oxygen required for the degradation of dead biomass
Ozone depletion potential	ODP	Translates the quantity of CFCs and halons emitted into a common measure to compare their contributions (relative to the freon CFC-11) to the breakdown of the ozone layer
Photochemical ozone creation potential	POCP	Translates the quantity of VOCs and nitrogen oxides emitted into a common measure to compare their contributions (relative to ethylene) to the formation of photochemical oxidants

Footnote

[1] This value is calculated based on the average CO_2 produced per kWh of electricity generated. The average depends on the mix of fossil fuel plants and renewable energy sources in electricity production.

ment (DfE) and other pro-environmental design and product development practices.

Focusing on environmental impacts

The information (or results) obtained from LCAs forms the basis of Environmental Product Declarations (EPDs). EPDs describe a product's most important environmental impacts during the manufacturing, usage and disposal phases. They can be certified by an impartial third-party organization, which gives the data additional credibility. ABB produces EPDs for all its core products, including VSDs, and information concerning resource utilization, energy consumption and losses, and emissions from the EPD for ABB's 250 kW ACS800 industrial drive is given in 2 to 4.

EPDs enable users to directly compare the environmental performance of different products, because the data is shown in terms of a functional unit (1 kW of rated output power in the case of the data presented in 2 to 4). EPDs also support manufacturers' efforts to enhance their products because they establish an environmental performance benchmark.

Even though EPDs focus on environmental impacts, they ignore the environmental benefits of using products like drives instead of a less efficient solution. According to the EPD information shown in 2 to 4, for example, an ABB industrial drive creates the greatest environmental impact during its usage phase. In fact a VSD can easily halve energy consumption in many applications, compared with the alternative of running the motor at full speed and then restricting output. Unfortunately the energy saved and emissions avoided by using a drive are not taken into consideration in the EPD in any way. Given the scale of the benefits – it is estimated that in 2008 alone the worldwide installed base of ABB drives saved around 170 TWh or about 142 million tons of carbon dioxide[2)] – this is a significant drawback to EPDs. One proposal to address this shortcoming is to determine the ecological payback of products.

In Europe it has been calculated that if VSDs were used in motor-driven systems, annual savings in electricity consumption totaling 50 million MWh could be achieved.

Ecological payback

Determining ecological payback is a new approach to the assessment of the lifetime environmental effects of products, which takes into account both their positive and negative environmental impacts. Natural capital – ie, natural resources – is consumed both in the manufacturing and disposal phases. However, by using eco-efficient products and processes such as drives in place of older, inefficient

2 Environmental Product Declaration (EPD) data for ABB's industrial drive, ACS800, 250 kW: resource utilization. Negative figures for the disposal phase reflect reuse or recycling.

	Manufacturing phase unit / kW	Usage phase unit / kW	Disposal phase unit / kW
Use of non-renewable resources			
Coal kg	0.66	560.8	–0.46
Aluminum (Al) kg	0.06	0.00	–0.00
Copper (Cu) kg	0.12	0.00	–0.11
Iron (Fe) kg	0.61	0.00	–0.49
Manganese (Mn) kg	0.00	0.00	0.00
Natural gas kg	0.18	65.35	–0.02
Uranium (U) kg	0.00	0.02	0.00
Oil kg	2.26	58.51	–0.06
Use of renewable resources			
Hydropower MJ	0.04	109	0.00
Wood kg	0.02	28.83	0.00

3 EPD data for ABB's industrial drive, ACS800, 250kW: energy consumption and losses

	kWh / product			kWh / kW		
Energy form	Manufacturing phase	Usage phase	Disposal phase	Manufacturing phase	Usage phase	Desposal phase
Electrical energy	57.0	625,331	–	0.23	2,501	–
Heat energy	31.1	–	–	0.12	–	–

4 EPD data for ABB's industrial drive, ACS800, 250kW: emissions

Environmental effect	Equivalent unit	Manufacturing phase	Usage phase
Global warming potential (GWP)	kg CO_2 / kW	3.65	1,570
Acidification potential (AP)	kmol H^+ / kW	0.00	0.27
Eutrophication	kg O_2 / kW	0.05	18.20
Ozone deleption potential (ODP)	kg CFC-11 / kW	0.00	0.00
Photochemical oxidants (POCP)	kg ethylene / kW	0.00	0.27

Footnote

[2)] This value is specific to the energy generated by fossil-fuel power plants, and is determined on the basis that the amount of CO_2 emitted by a fossil fuel powered electricity plant is approximately 0.84 tons/MWh. Wind turbines, nuclear power or hydropower plants produce little or no CO_2.

solutions, it is possible to considerably reduce the overall load on the environment. The ecological payback value shows how long a product has to be used in order to compensate for the one-time environmental burden of its manufacture and disposal. Basically it can be considered as the environmental payback of a product.

5 Ecological payback (in days) for three types of ABB drives by environmental impact categories. Assumptions: drive provides 50 percent energy savings in typical pump or fan application using an average EU-25 electricity mix.

Product	Power kW	GWP	AP	EP	POCP
ACS140	0.75	6	6	8	15
ACS350	7.5	1.1	0.9	1.2	1.3
ACS800	250	0.5	0.4	0.9	1.0

Source: Tampere University of Technology

5 shows ecological payback in days for three different ABB drives. The payback times are short, decreasing with increasing power ratings. For a 250 kW drive (ACS800), for example, the payback time is calculated as one day.

Determining ecological payback is a new approach to the assessment of the lifetime environmental effects of products. It takes into account both their positive and negative environmental impacts.

Negative carbon footprints

Emissions data from the EPD of an ACS800 250 kW drive shows that its manufacturing carbon footprint is 3.65 kg CO_2/kW or 912.5 kg CO_2 in total 4. The information given in 5 for the same drive indicates that ecological payback in terms of global warming potential (GWP) is 0.5 days. In other words, by operating the drive for just half a day it is possible to avoid enough emissions to fully compensate for the carbon impact of manufacturing. The footprint then "turns negative" as the drive will continue to benefit the environment by saving emissions throughout its lifetime. In fact, an ACS800 industrial drive will typically provide a total lifetime savings of around 7,500 MWh or 3,800 tons of carbon dioxide emissions.

In a world where AC induction motors are still the undisputed "workhorses of industry," VSDs can play a very important role in reducing energy costs and carbon emissions.

A power generating water pumping station

A German utility company in Stuttgart uses ABB industrial drives to control pumps that can also operate in turbine mode to generate power. Water is abstracted from Lake Constance in southern Germany and, after treatment, is piped around 120 km to a storage tank in Rohr on the outskirts of Stuttgart. From Rohr the water is piped to the pumping station at Gallenklinge, where it passes through the pumps/turbines and is then stored in a tank before being fed into the Stuttgart network. The height difference (head) between Rohr and Gallenklinge is 120 meters.

As part of a recent upgrade project, three ABB industrial drives (ACS800, 400 kW) were installed at the pumping station. The drives used are regenerative drives, which have an active supply unit to allow full power flow in both motor and generator modes. The drives are also fitted with EMC filters for the first environment, and the power generated is supplied to the regular grid.

Emissions data from the EPD of an ACS800 250 kW drive indicates that ecological payback in terms of global warming potential is half a day.

The drives operate 315 kW, 400 V motors, and the pumps are arranged in a parallel configuration for redundancy. ABB's intelligent pump control (IPC) software in the drives provides additional functionality, including energy optimization, master change, PID control, and pump priority control. The pumps are normally used in turbine mode, with pumping mode only used in emergency. Output power is typically 200 kW. The pumping station previously used turbines with pitch-controlled blades, but VSDs have been found to offer a more economic solution with greater flexibility.

Cement producer cuts energy and maintenance costs

Castle Cement's Padeswood Works in North Wales, United Kingdom, home to one of Europe's most modern cement kilns, uses ABB industrial drives to operate fans. These include a 2 MW induced draft (ID) fan, a 750 kW exhaust fan, and a 560 kW cooler fan. The fans have to be controlled to accommodate differing flow requirements due to changing atmospheric and process conditions, and changing ventilation needs. A further four fans – rated at 110, 160, 200 and 250 kW – push air into the grate cooler to reduce the temperature of the hot clinker to a set point.

Fan control was previously implemented by means of slip rings and DC motors, which require regular maintenance. With the installation of ABB industrial drives and the replacement of the slip rings and DC motors with maintenance-free AC motors, the plant has realized savings of up to 30 percent on the total energy costs of the fans, together with major savings in maintenance costs on the old type motors.

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Footnote

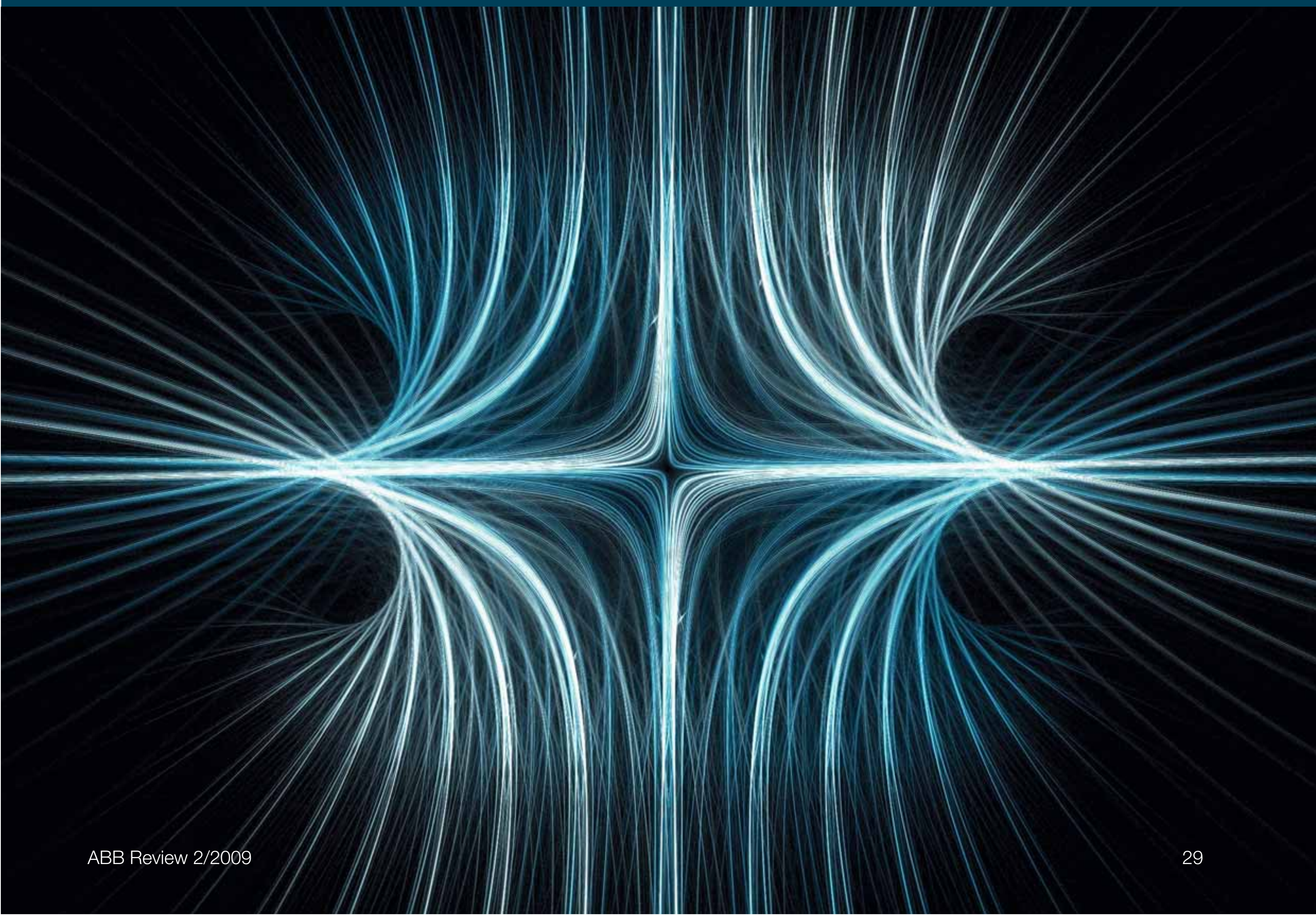
[3] This calculation has been made assuming a typical service life of 10 years, 6,000 running hours per annum and average energy savings of around 50 percent.

The attraction of simplicity

Permanent magnet machines are here to stay

Jussi Salo

It is interesting to consider that many system components that we take for granted started off as workarounds. Not long ago, most readers would have taken it for granted that a large electric motor needed a gearbox to convert its speed and torque, and also an excitation system to provide the magnetic fields. Sometimes, a redesign can help eliminate these workarounds and reduce the system to elegant simplicity. Progress with magnetic materials means that low-speed high-torque drives can now be realized with permanent magnets, permitting the elimination of both the excitation and the gearbox. This approach is permitting energy saving and manifold other advantages in applications such as industrial drives, Azipod marine propulsion systems and wind turbines.



The concept of using permanent magnets (PM) for excitation in electric machines has been around for a long time. During the last 10 years, however, PM technology has advanced to be a technically and economically feasible solution, especially for slow speed high torque direct drives.

PM technology has some clear advantages over other excitation methods for electrical machines. Its widespread application has only become feasible recently, however, thanks to improvements in permanent magnet technology and decreases in their costs. ABB has developed PM technology-based products, especially for low-speed high-torque applications, as are found, eg, in process industries, ship propulsion and wind power.

During the last 10 years, PM technology has advanced to be a technically and economically feasible solution.

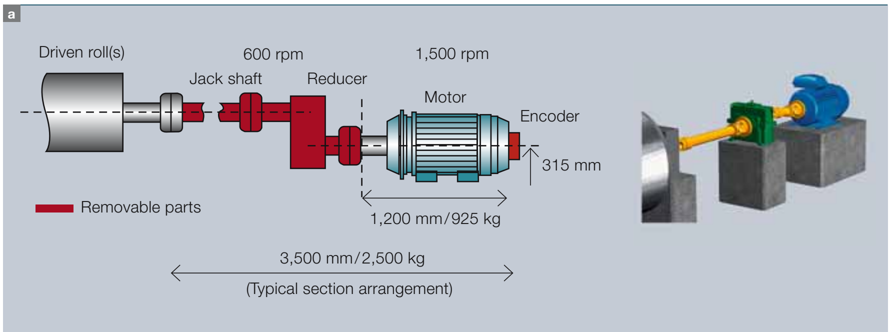
Further gains can be made by adopting all-electric direct drive technology, eliminating the gearbox and its accessories 1. The removal of these features leads to lower losses and better reliability of the drive as a whole. A three-stage gearbox in a 3 MW wind turbine decreases overall efficiency by about three percent. Additionally the elimination of the gearbox and jackshaft saves space on the factory floor.

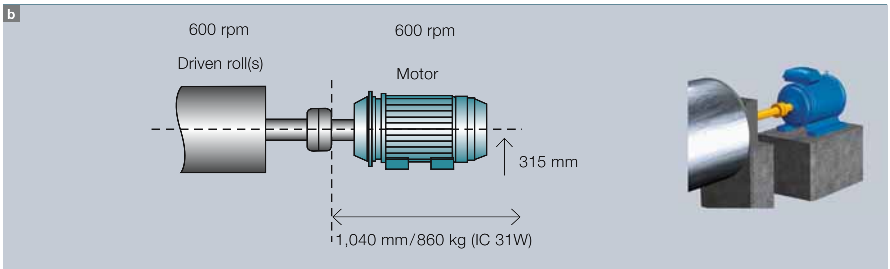
A PM machine can be made as robust and simple as the equivalent squirrel-cage induction motor. When such a PM machine is used with an ABB direct torque control (DTC) variable-speed converter, there is no need to use a speed encoder to provide feedback of the rotor speed. The elimination of this potentially unreliable component further increases the reliability of the PM direct drive solution. Such a drive can offer a better availability than other presently available technologies in the low-speed, high-torque range. Thanks to this increased availability, the life-cycle costs can also be reduced.

PM machines in direct drive technology

ABB has been producing permanent magnet (PM) machines for almost 10 years now. A PM machine is a synchronous machine. It normally has three or more stator phases in the stator winding. Permanent magnets mounted in the rotor create a practically constant flux in the air gap. This "locks" to the rotating flux created by the stator windings. The PM machine thus runs in synchronism.

1 Drive configurations with conventional induction motor drive, gear and jackshift a, and the direct drive b





The shaft height of the machines delivered varies from 280 mm motors to 2,500 mm wind generators. The M3BJ, AMZ and AMG permanent-magnet machine product series have proven themselves as mature products.

A PM machine can be made as robust and simple as the equivalent squirrel-cage induction motor.

Electrical machines with a low number of poles, designed for a higher rated speed, can be operated at low speeds if they are supplied with a low frequency. However, such an application is not efficient as the converter's output frequency is much lower than its rated frequency range. At such a low frequency, the power switches have to be over-dimensioned in order to withstand the resulting switching losses. Therefore, machines with a high number of poles are generally preferable for low-speed applications.

Induction machines designed to run at 750 to 3,000 rpm are not particularly well suited for low-speed direct-drive operation as their efficiency drops with the reduction in speed. They may also be unable to deliver sufficiently smooth torque across the lower speed range.

The power factor of an induction machine also drops with higher pole numbers (due to the increased leakage inductance). Therefore, induction machines with high pole numbers are not really suitable for low-speed direct drives.

These problems explain why gearboxes were added for such applications, permitting the machines to run more comfortably at higher speeds. The superior performance of PM machines in low-speed high-torque applications changes this, and permits the gearbox to be eliminated.

Reduced losses

One notable advantage of using permanent magnets for excitation is that there is no need to deliver excitation power from the grid through the converter to the machine, and thus the power required for excitation is saved. Also, converter losses are reduced, as the reactive current of excitation power is avoided. This gives some extra margin of load capacity for the inverter compared to a drive for an induction machine of the same output power.

The superior performance of PM machines in low-speed high-torque applications permits the gearbox to be eliminated.

Harmonic components of the inverter voltage cause eddy currents on the surface of the PM rotor and magnets. These can be significantly reduced through suitable design methods and constructions. Most of the losses of the PM machine are generated in the stator windings and stator core. As a result, the temperature of the PM rotor in load conditions is quite low compared with electrically excited machines. Consequently, the temperature of the bearings is often lower. Lower bearing temperatures result in longer life of both the lubricant and the bearing itself.

DTC without encoders

Low-speed high-torque direct-drive applications usually demand control of torque and speed. The speed of a synchronous machine, such as a PM motor, can only be controlled with a variable-speed drive. Furthermore, the PM machine control must be specifically developed for permanent-magnet flux control. ABB's direct torque control (DTC) method has been enhanced for variable-speed PM machine drives.

Low-speed direct-drive applications often come with high demands on controllability and dynamics. These can be met by using ABB's DTC drive technology. When using a PM machine, it is possible to obtain the required high-performance operation without a speed encoder, as accurate calculation of the angle position and speed of the rotor are possible without such a device.

Currently ABB has low-voltage ACS800 and medium-voltage PCS6000 drives capable of supplying PM machines with DTC control.

Higher system efficiency and availability

It has already been mentioned that the PM machine direct-drive solution can have higher overall system efficiency than a conventional jack shaft, gearbox and electric machine combination, because the associated losses are avoided. The efficiency advantages do not end here, however.

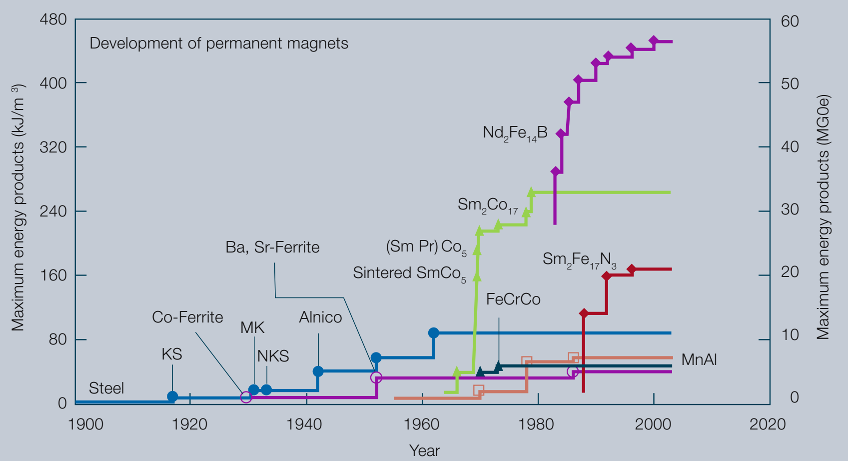
The construction of a PM machine can be as simple and robust as that of a cage induction machine. The absence of a gearbox, associated accessories, jack shaft, extra couplings and speed encoder means PM direct drives have a minimum amount of rotating parts and a minimum need of maintenance. This leads to high system efficiency when compared with other currently available technologies.

All these factors lead to increased availability, energy savings and minimized life cycle costs.

Development of permanent magnets

Since 1960 the development of permanent magnets has advanced at a rapid pace 2. Permanent magnets see widespread use in low-power motor drives such as in hard disk drives and in consumer electronics. The use of permanent magnets in electrical machines has not been common until last two decades. This was primarily due to the relatively high price

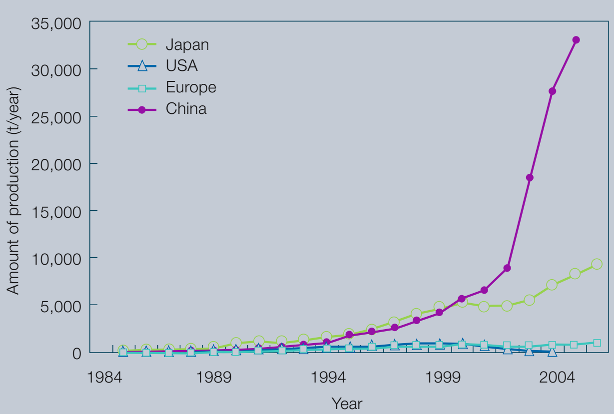
2 Development of the energy product of permanent magnets



Source: Masato Sagawa, NdFeB magnets: Past, Present and Future, Prizztech Seminar on Advanced Magnetic Materials and their Applications 10.–11. 10. 2007 Pori

Energy product is a measure of the strength of a magnet, expressed as the product of its flux, B (measured in Gauss) and field intensity, H (measured in oersteds or amps per meter). The units for energy product are megagauss-oersteds (MGOe) or kJ/m³.

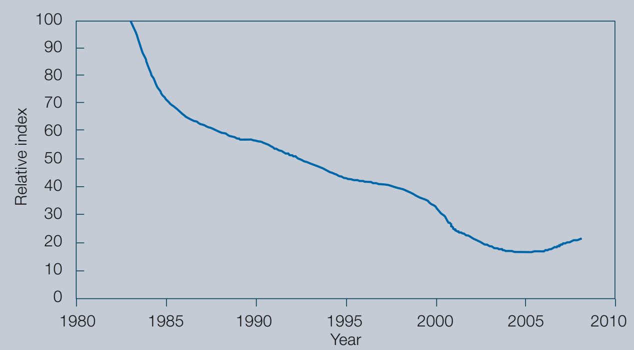
3 Development of production of sintered NdFeB magnets



Source: Masato Sagawa, NdFeB magnets: Past, Present and Future, Prizztech Seminar on Advanced Magnetic Materials and their Applications 10.-11.10.2007 Pori)

Sustainability and energy

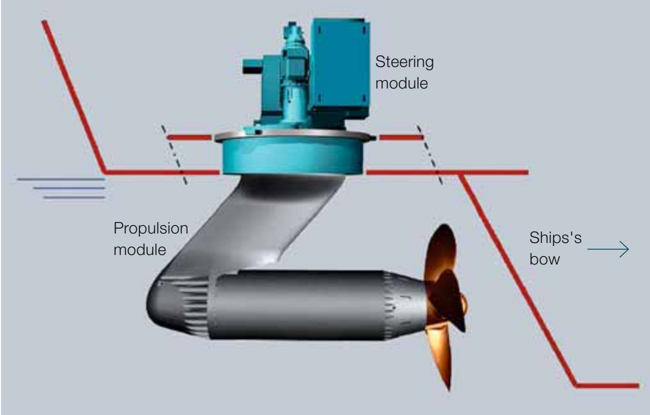
4 Development of relative price of sintered NdFeB magnets



The price of 1983 is used as a base value

Source: Magnews Summer 2008

5 ABB's Compact Azipod uses a permanent magnet motor



and manufacturing costs of magnet material.

Neodymium (Nd) Iron (Fe) Boron (B) magnets were invented in 1987. NdFeB is now the newest and most powerful magnetic material on the market. NdFeB has high values of flux density at very high values of magnetization. It is also extremely resistant to demagnetization. Furthermore, NdFeB is less costly and brittle than samarium cobalt, another rare earth material, that was used widely in the 1980s. Hence NdFeB magnets are normally used in ABB PM machines.

Rare earth metal production started in China in the mid 1980s. Strong market penetration caused the prices of the rare earth metals used in the production of permanent magnets to collapse 3. NdFeB is currently the most important permanent magnet material. In addition to Nd, Dysprosium (Dy) and Terbium (Tb) are also needed. The price of NdFeB magnets 4 has decreased significantly since the 1980s, but now after a bottom touch, the prices are increasing again; however at a reasonable rate.

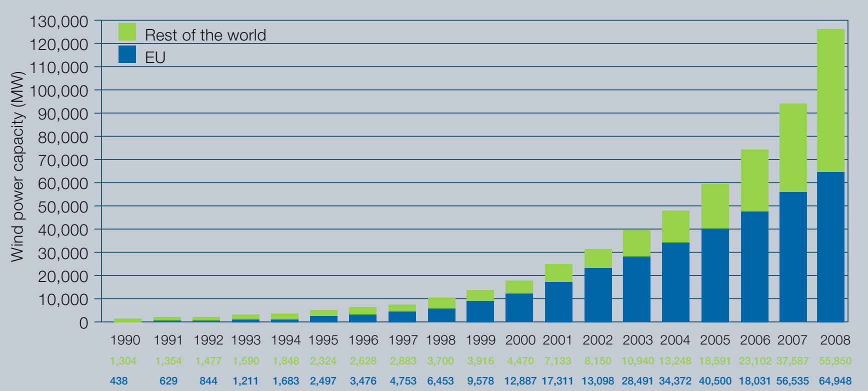
The higher availability of the PM direct drive has the additional advantage that it permits a reduction in inventory costs as fewer spare parts are needed.

The cost of NdFeB magnets of a large 2 to 4 MW direct-drive wind turbine PM generator is about 15 to 30 percent of the total material costs of the generator. The reduction in prices of NdFeB magnets at the beginning of the first decade of the 2000s has made large PM machines more attractive than ever before for low-speed direct-drive solutions.

PM motors in the process industry

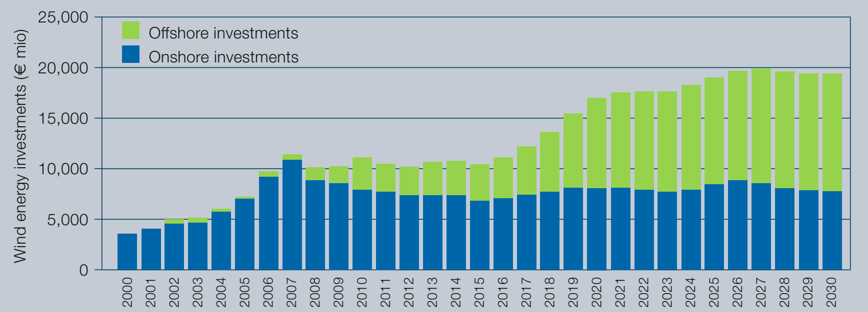
High-accuracy low-speed drives are widely used in process industry. PM direct-drive technology can be used to eliminate gearboxes across a wide range of industries. For example, there are tens of rolls in a paper machine driven by a conventional solution: Every variable-speed drive with a normal-speed induction motor in such

6 Growth opportunity: Global cumulative wind power capacity 1990–2008



Source: EWEA, Wind Energy Scenarios up to 2030

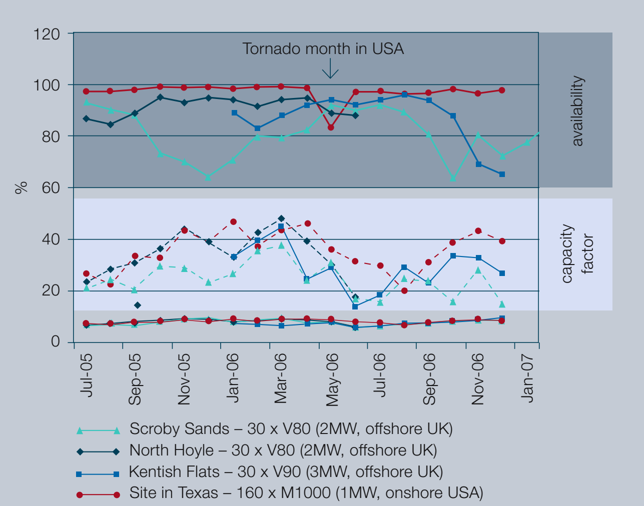
7 Scenario of wind energy investments in the EU up to 2030



Source: EWEA, Wind Energy Scenarios up to 2030).

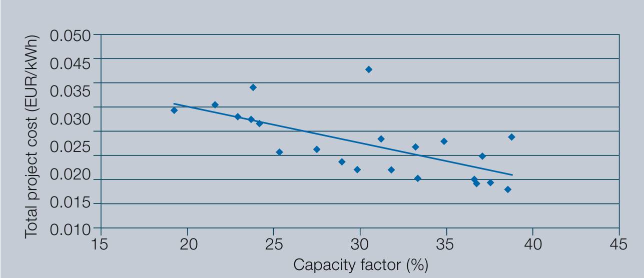
an application has a pulse encoder, jack shaft and gearbox. The PM direct drive solution without these extras is particularly beneficial in the paper industry, where poor reliability of feedback devices is a cause of unplanned production breaks. The higher availability of the PM direct drive has the additional advantage that it permits a reduction in inventory costs as fewer spare parts are needed.

8 Availability, capacity factor and wind speed of four wind farms



Source: Fabio Spinato, The Reliability of Wind Turbines

9 Total project cost per kWh vs. capacity factor



Source: Garrad Hassan, European Wind Farm Project Costs History and Projections 2008 Study

PM technology in propulsion

The ABB podded electric machine propulsion concept "Azipod" for ships has been on the market for 20 years now. During that time, in addition to being fitted to large cruise vessels, Azipod has rapidly gained popularity in other types of vessels such as cable layers, dredgers, shuttle tankers, chemical and product tankers, support vessels, motor yachts, drill ships and semi-submersible rigs.

In Azipod technology, the electrical motor is mounted in a bulb, which is attached to the hull of the ship, and these together form the main propulsion system. The speed of the motor and direction of the propulsion force is controlled in relation to the ship. The typical power range of these motors is 400 kW to 20 MW. One ship is normally equipped with between one and three propulsion units, and rigs equipped with dynamic position systems may use up to 10 units. Azipod allows excellent ship maneuverability, low vibration and noise levels, high efficiency, low emission and passenger comfort.

Permanent magnet motor technology has been used in the development of a highly standardized modular concept known as "Compact Azipod" **5**, which has been designed for a propulsion power range of between 400 to 5,000 kW. Permanent magnets and DTC have been the main factors for improving the performance and extending the applicability of Compact Azipod.

In PM Azipod solutions, the motor module can be cooled by the surrounding seawater, which would not be possible with high rotor losses.

There are no excitation losses in the PM rotor and hence most of the losses are generated in the stator winding and stator core, from where they can more easily dissipate. This permits PM technology to provide a higher power density. In PM Azipod solutions, the motor module can be cooled by the surrounding seawater, which would not be possible with high rotor losses. Furthermore, this approach permits the pod housing diameter to be kept small, providing improved hydrodynamic efficiency. This further increases fuel efficiency.

PM machines in wind power generation

The last 20 years have witnessed a phenomenal growth in the wind energy business **6**. In this time, it has developed from experimental pioneering to mature global manufacturing. Today, wind power is the most promising source of new renewable energy.

Wind energy capacity is expected to grow much faster offshore than onshore **7**. There are various reasons for this: It is easier to find space for a big offshore wind farm than for a big onshore wind farm. Offshore wind farms do not disrupt social communities in the way that onshore installations might do. It also expected that available wind resources are substantially more significant offshore than onshore.

In order to get the most energy out of available wind, the capacity factor should be high. The capacity (or load) factor of a wind turbine or wind farm is a measure of how much electricity is generated yearly compared with the installed capacity. The capacity factor is not a direct reference for the "windiness" of a particular region or site. This is because the size of the turbine rotor, the height of the tower and the availability of the turbine also have significant influence on energy capture.

It can be seen from **8** that where the availability of offshore wind farms rises above 90 percent, their capacity factor often exceeds that of the onshore wind farms.

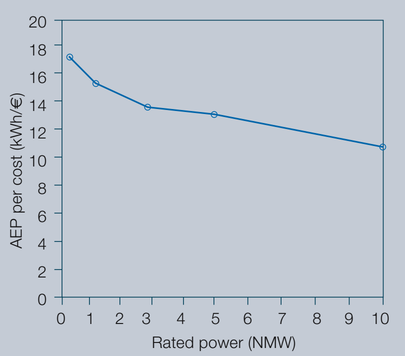
Availability is a function of machine reliability. A system can have a high reliability, but if appropriate maintenance is not conducted speedily, then the wind turbine can have a low availability.

Availability can be defined as a function of MTBF (mean time between failure) and MTTR (mean time to repair), so that Availability = MTBF/(MTBF+MTTR). MTBF is a measure of reliability and MTTR is measure the repair time, which is affected by availability of spare parts, personnel and equipment needed for repair and accessibility of the turbine.

The total project cost and cost of energy are affected by the capacity factor 9. A larger turbine can capture more energy out of wind, thus making the price of generated energy cheaper 10.

There is an obvious trend to build larger and larger wind turbines and position them further offshore. However, recent studies have shown that more than one failure per turbine per year is common and reliability is lower for larger turbines [1]. Such poor reliability will be problematic in offshore installations, where more than 0.5 failures per year are not acceptable.

10 The annual energy production (AEP) per cost as a function of rated power



Source: Hui Li, Zhe Chen, Design Optimization and Comparison of Large Direct-drive Permanent Magnet Wind Generator Systems, Proc. ICEMS 2007).

There are no excitation losses in the PM rotor and hence most of the losses are generated in the stator winding and stator core, from where they can dissipate more easily.

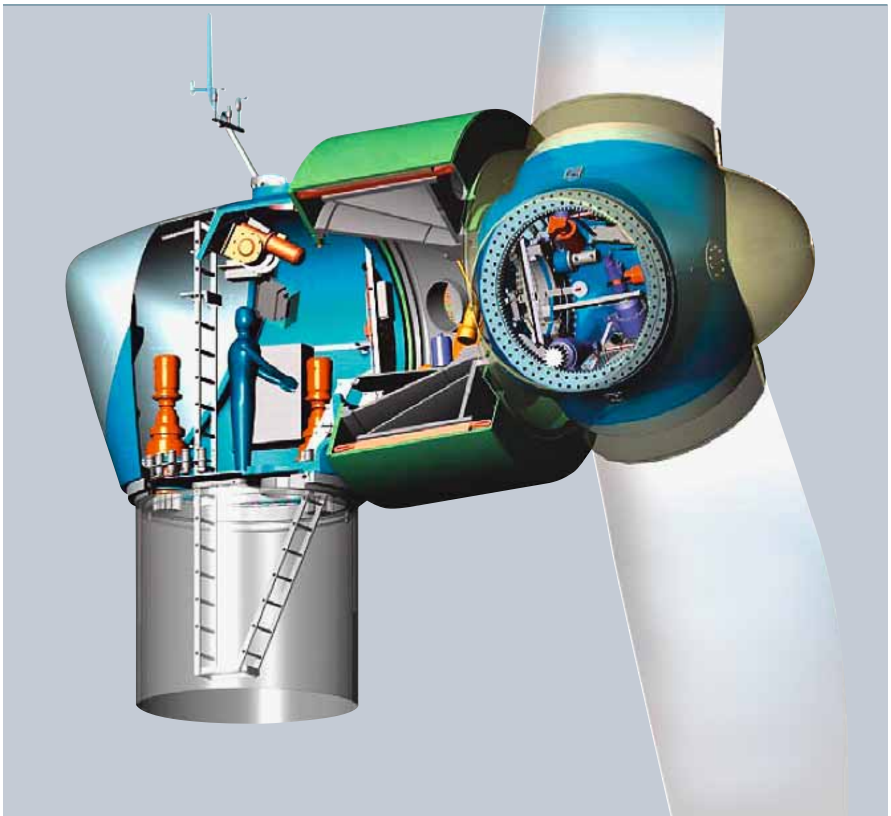
Reliability issues are mainly concentrated in the drive train and electrical subassemblies. Gearboxes for 3 MW and more are gaining in reliability, but gearbox failures do cause the most significant downtime and costs. Electrical components (except generators) cause relatively little downtime but their repair also causes high costs, especially in offshore locations.

The share of direct-drive turbines has been 13 to 15 percent of all yearly installed capacity over the last 10 years.

It may come as a surprise that the direct drive is not always intrinsically more reliable than an indirect drive. This is because the technology is still relatively new, and in some respects still developing.

Before even larger offshore wind turbines become feasible, their availability has to increase further. It is probably easier to improve the reliability of electric systems than that of mechanical systems. It is therefore expected that a permanent-magnet direct-drive wind turbine will have higher availability than a traditionally geared electrically excited one.

The Zephyros Z72 wind turbine with an ABB Direct Drive PM generator (green part)



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References

[1] **Spinato, F.** (2008). The reliability of wind turbines. PhD thesis, Durham University.

BORDLINE® M

A very high-efficiency AC/DC/DC converter architecture for traction auxiliary services

Antonio Coccia, Francisco Canales, Hans-Rudolf Riniker, Gerold Knapp, Beat Guggisberg

The power needs on a train are manifold. The traction itself requires power, but so do many auxiliary consumers ranging from traction excitation, to on-board lighting, heating and air conditioning. Space and cost constraints are increasingly leading to demands for a single converter able to cover all these needs. Such a converter must supply both AC and DC outputs. Its output is required to meet high standards, it must nevertheless deal with a wide range and quality of input power conditions.

ABB Review takes a look at some of the technologies behind the company's BORDLINE® M series of converters and some of the challenges involved in its design.

The new generation of traction power supplies must not only meet load-characteristic demands, but also be able to process large amounts of energy (due to the increasing number of loads, caused for example, by rising demands on on-train comfort) and must do this with very high efficiency, reliability and power density. Moreover, cost is a very important factor. In high power-density building block converters, it is usually necessary to operate semiconductor devices at high switching frequencies. The downside of this is that increased switching frequencies bring with them higher switching losses. In switch-mode PWM (pulse width modulation) power supplies, the switching losses can be so high that they make the operation of the system at very high frequencies unfeasible, even when soft-switching techniques are used.

Resonant-mode power supplies[1)] address all the aforementioned issues through their lower switching losses [1]. The use of such architectures represents an interesting option to those applications requiring the performance enhancements outlined above.

In today's traction applications, insulated-gate bipolar transistors (IGBTs) are the most suitable switching devices for meeting the voltage and current requirements and also feature very high insulation voltage levels. For those devices operating at high switching frequencies, zero-voltage switching (ZVS) can be a valuable option to enhance the converter efficiency. This approach reduces to zero the switching energy associated with both the high parasitic capacitance values characterizing the modules (affecting the turn-on losses) and the reverse recovery of anti-parallel diodes (associated with their turn-off).

For a nominal input voltage of 1,000 Vrms AC, the corresponding operating range varies between 700 Vrms and 1,200 Vrms.

One of the biggest challenges facing designers of power supplies for traction applications is the extremely wide input-voltage range at the converter input terminals. This variance should not have any effect on the overall system performances and efficiency during all the different operating conditions. The possible input voltage variation range for all possible electric traction systems are shown in 1. For a nominal input voltage of 1,000 Vrms AC, the corresponding operating range varies between 700 Vrms and 1,200 Vrms – a very large range.

Although several papers have been published on the topic of wide input-voltage compensation methods for power supplies, not so many can be found on how to deal with such broadly varying operating conditions.

For an extreme input voltage variation as shown in 1, the converter optimization design remains a concern wherever resonant topologies are used. As a matter of fact, the wide input voltage range might result in high levels of circulating energy. This reduces the overall efficiency considerably, and also the converter power density.

In today's traction applications, IGBTs are the most suitable switching devices for meeting the voltage and current requirements and also feature very high insulation voltage levels.

Several solutions have been proposed in the past attempting to meet these requirements and also the output load variations. The conventional series-resonant converter operates with ZVS for the active devices when the switching frequency is above the resonant frequency. However, for wide

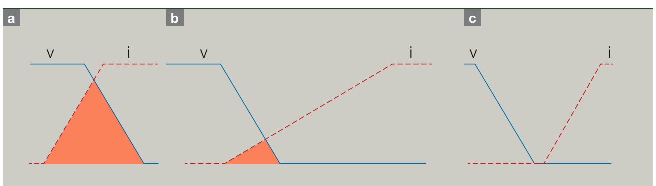
Footnote

1) As their name suggests, resonant-mode circuits use resonance effects to support them in forming their AC output.

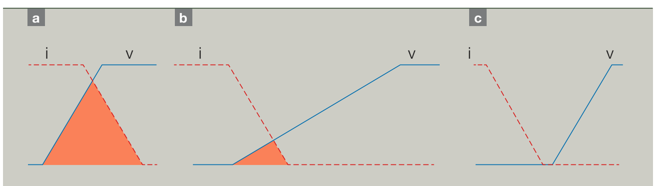
1 Line input voltage range for railway systems, from the EN50163 international standard. The broad input range creates special challenges.

EN50163, UIC550					
System voltage	Minimum not permanent	Minimum permanent voltage	Normal voltage	Maximum permanent voltage	Maximum not permanent
	Voltage Umin2 (V)	Umin1 (V)	Unom (V)	Umax1 (V)	Voltage Umax2 (V)
DC system	400	400	600	720	800
	500	500	750	900	1,000
	1,000 (900UIC 10 min)	1,000	1,500	1,800	1,950
	2,000 (1,800 UIC 10 min)	2,000	3,000	3,600	3,900
AC system	700 Vrms	800 Vrms	1,000 Vrms 16,67 Hz/50 Hz	1,150 Vrms	1,200 Vrms
	1,050 Vrms	1,140 Vrms	1,500 Vrms 50 Hz	1,650 Vrms	1,740 Vrms

2 Turn-on commutation mode: hard a, L in series b, soft c



3 Turn-off commutation mode: hard a, L in series b, soft c



variations of the input voltage and output load, the converter must operate with wide switching-frequency variations. This complicates the optimization of the converter [2,3].

Furthermore, in the case of high input voltages, as found in railway applications, the necessity to use devices with high-voltage-ratings aggravates the problem. The series connection of converters has been proposed to reduce the voltage stress across the main devices [4,5]. This permits the use of devices with a low-voltage rating, while maintaining the switching characteristic of the converters. However, an additional control strategy is needed to balance the input voltage across the input capacitors.

Setting out to minimize the complexity of the various approaches, the BORDLINE® M series converter presents a novel solution to mitigate the impact of a wide-input voltage range in the performance of AC/DC/DC isolated converters for traction auxiliary services. The units generate a galvanically isolated, constant direct voltage for charging batteries, as well as a sinusoidal three-phase voltage to drive AC motors. Optionally, the sinusoidal output voltage can be galvanically isolated. Here, the front-end power architecture is a three-level PFC (power factor corrector) converter, which follows the input voltage variations, guaranteeing a power factor close to unity under all operating conditions. The second converter stage is realized by means of a three-level LLC[2)] isolated resonant converter operated in ZVS and quasi ZCS (zero current switching) mode.

The series connection of converters permits the use of devices with a low-voltage rating, while maintaining the switching characteristic of the converters.

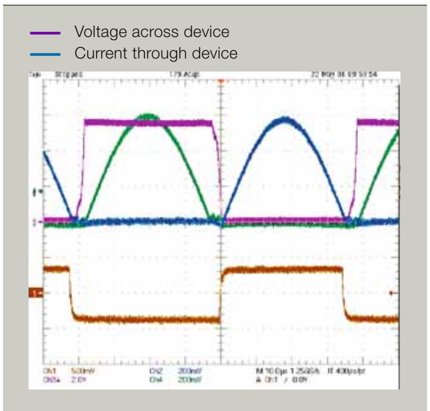
Hard switching versus soft switching

The commutation mode of semiconductor devices is usually classified as hard-switched, snubbered or soft-switched depending on the quantity of energy losses generated during the state transitions (turn-on or turn-off).

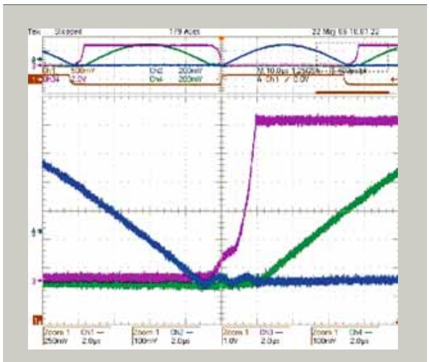
2 shows these three commutation modes. In hard switching 2a, there is a considerable area of overlap between the voltage across the semiconductor device and its commutated current. 2b illustrates the typical commutation of a device with an L (inductor)-type snubber circuit in series with the semiconductor: The snubber circuit reduces the current's rate of change (dI/dt) and this helps reduce the overlap between the voltage and the current, significantly reducing the switching losses. 2c shows a typical soft-switched commutation (ZVS, zero-voltage switching). An external circuit is used to practically eliminate the overlap. The semiconductor does not start conducting until the voltage across its terminals has already reached zero. Turn-on losses are thus eliminated.

4 Soft-switching behavior of a 1,700V IGBT with ZVS and ZCS:

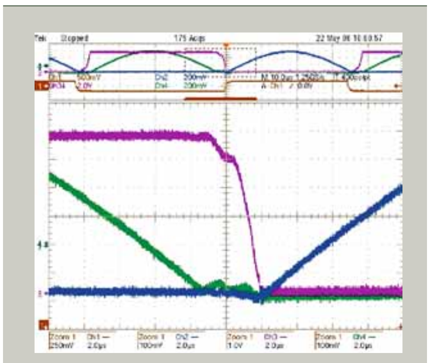
a Switching cycle



b Turn-off transition with ZCS



c Turn-on transition with ZVS



Footnote

2) An LLC is a resonant circuit using a capacitor and two inductances; Both of them could be the winding parameters of the transformer.

The turn-off transition 3 is comparable. The hard turn-off 3a generates the greatest losses. The snubbered mode 3b is achieved by means of a C (capacitor)-type snubber connected in parallel to the device, reducing the device dV/dt. Finally, 3c shows the soft-switched turn-off transition (ZCS, zero-current switching).

A soft-switched turn-on/turn-off transition for an IGBT device is shown in 4.

AC/DC/DC topology description

The block schematic of the BORDLINE M series power architecture, presented in 5, combines high performances with high reliability while reducing costs. Here both PWM and resonant technologies were adopted so that high conversion efficiency could be achieved under all operating conditions.

One of the biggest challenges facing designers of power supplies for traction applications is the extremely wide input-voltage range at the converter input terminals.

The first converter stage is realized by means of a direct AC/DC step-up converter working in PWM hard-switching mode, while the second DC/DC isolated stage is realized as a three-level half-bridge configuration and works in LLC resonant mode. On account of the resonant technology, the second converter stage is able to guarantee zero-voltage switching (ZVS) and quasi zero-current switching (ZCS) in all operating conditions, hence significantly reducing the switching losses in the silicon devices. In the third stage, an output three-phase inverter and a DC/DC battery charger are connected to the secondary DC-Link.

Three-level PFC boost converter

The three-level PFC boost converter operating in hard-switching mode receives a variable input voltage (in this case study, between 700 Vrms and 1,300 Vrms). Using duty-cycle modulation, a constant voltage is produced at the output terminals. This feeds the second resonant stage, always guaranteeing an input-line current that is sinusoidal and in phase with the line voltage. The three-level PFC boost converter is realized by means of an input diode-bridge rectifier and a three-level DC/DC converter. A boost inductor (Ls) is used to store the line energy for the boosting action, while an input EMI (electromagnetic interference) filter is needed to meet all the current harmonics injection standards.

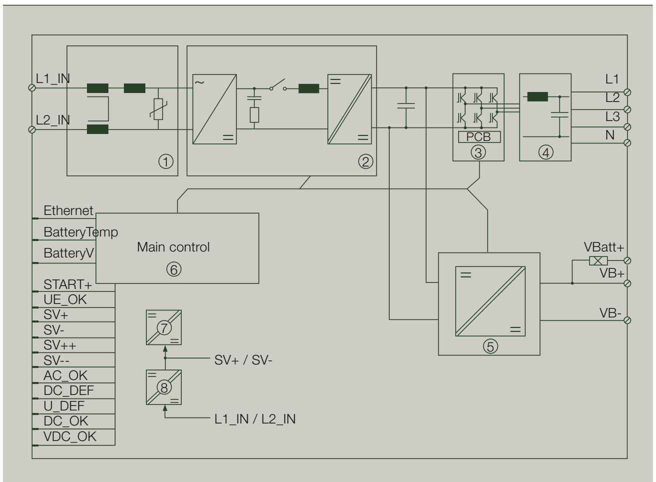
The IGBT switching frequency has been set low in order to limit semiconductor losses. Using the possibility of interleaving the firing signals sent to the semiconductors on the three-level boost converter (by 180° with respect to the switching period), the equivalent switching frequency for the entire five-level converter as seen by the network is higher than 6.5 kHz. Thanks to this equivalent increase of the switching frequency, it is possible to reduce the size of both the boost inductor (which is a quarter the size of that for a conventional two-level boost converter) and the EMI input filter, whose size is defined by the level of harmonic-current mitigation required by standards.

By implementing an active compensation it is possible to mitigate all the problems connected to the undesired harmonics.

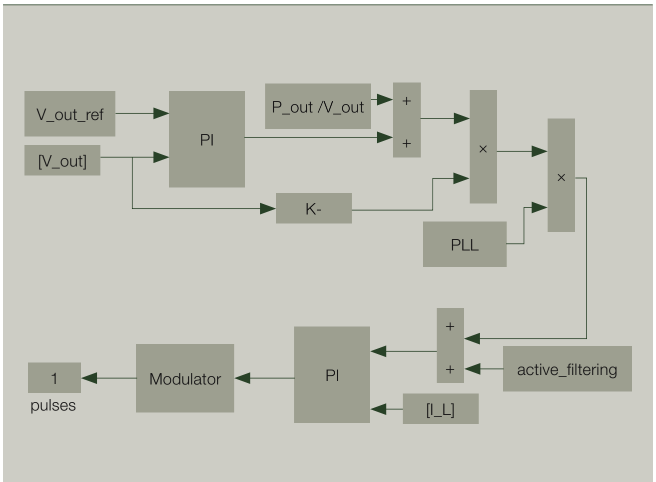
PFC converter control

The control system makes use of standard PI regulators 6. A standard cascaded control scheme guarantees, by means of an "outer and slower" loop, the desired output DC-link voltage regulation, and, by means of an "inner and faster" loop, a boost inductor current control. This permits the required high power factor to be achieved on the line side. The line-voltage synchronization (PLL), needed for the inner current control, is realized immediately after the input diode bridge. A duty-cycle reference signal (sinusoidal reference) is then compared to two triangular carriers (whose frequencies are equal to the desired devices' switching frequency), so that two interleaved firing signals can be obtained for the three-level boost converter devices. Two additional feed-

5 Converter layout

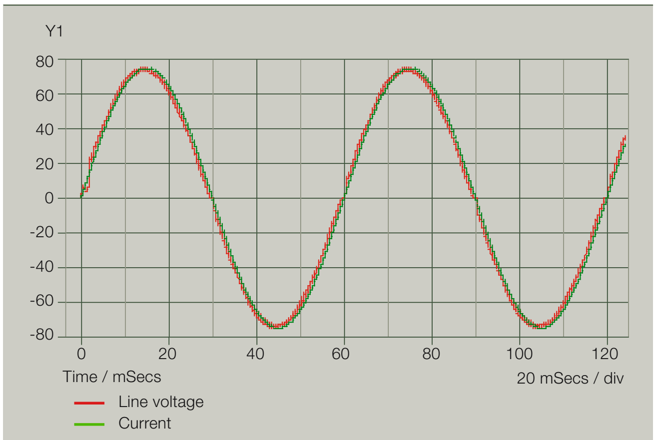


6 Block diagram of the power factor correction (PFC) control strategy

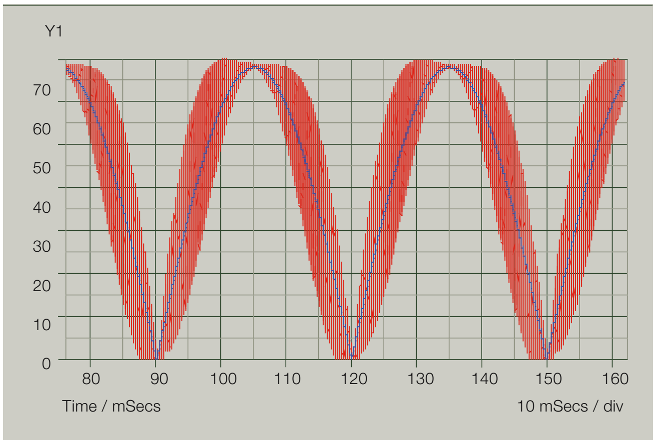


7 PFC simulation results at nominal output power and voltage

a Line voltage and current



b Boost converter current and its reference

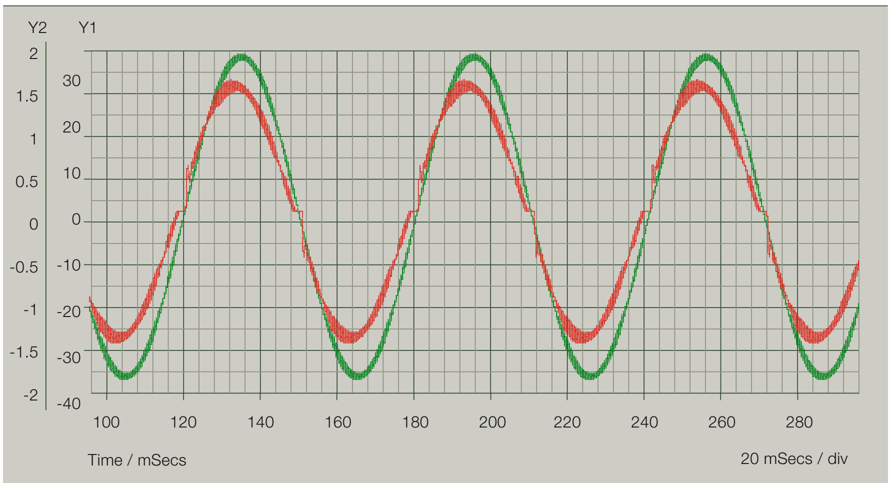


forward actions (one on the reference current and one on the reference line frequency) enable faster time responses during control to achieve a steady-state operating mode.

The increased equivalent switching frequency makes it possible to reduce the size of both the boost inductor and the EMI input filter.

Simulations were performed under the following conditions: 50 kW output power, 700 Vrms input voltage and 2,000 V DC-link set-point voltage 7. The implemented control scheme shows quite good behavior for all the load conditions in the whole input voltage range, also at light load conditions (output power less than 20 percent of the rated power) and high-input voltage (higher than 1,200 Vrms). Under these conditions, the line currents usually present quite a high level of harmonic distortion, but by implementing an active compensation of the undesired harmonics it is possible to mitigate all the problems connected to the undesired harmonics and be fully compliant to the international standards of electromagnetic pollution on railway networks. The line current is sensed (it can also be the current of the boost inductor, with the switching frequency harmonic properly filtered), and this value is added to the reference sinusoidal current that theoretically should circulate in the network. This modified reference signal is then compared with the actual boost current and processed by a PI controller. 8 compares the compensated line current with the line voltage.

8 PFC simulation results at light load conditions (30 percent output power) and high-input voltage (1,300 Vrms)

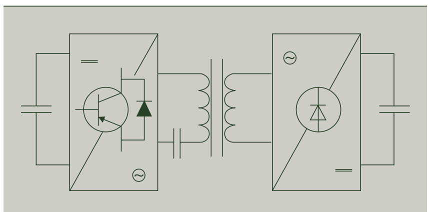


On account of the resonant technology, the second converter stage is able to guarantee zero-voltage switching (ZVS) and quasi zero-current switching (ZCS) in all operating conditions.

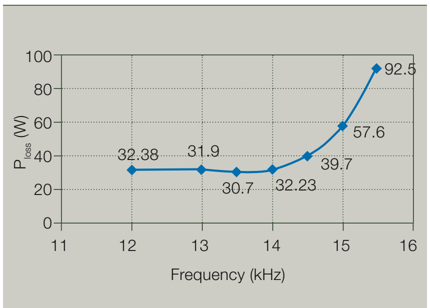
Isolated three-level half bridge

The resonant converter stage implementing the galvanic isolation 9 consists of several elements; an input DC/AC three-level front end converter (receiving a stabilized DC voltage); a resonant circuit with three passive elements (implemented with external resonant capacitors and parasitic impedances of the transformer); a galvanically isolated transformer of the desired turns ratio in order to guarantee a proper output DC-voltage; and an output diode bridge rectifying the transformer output voltage.

9 Block schematic of the implemented second converter stage

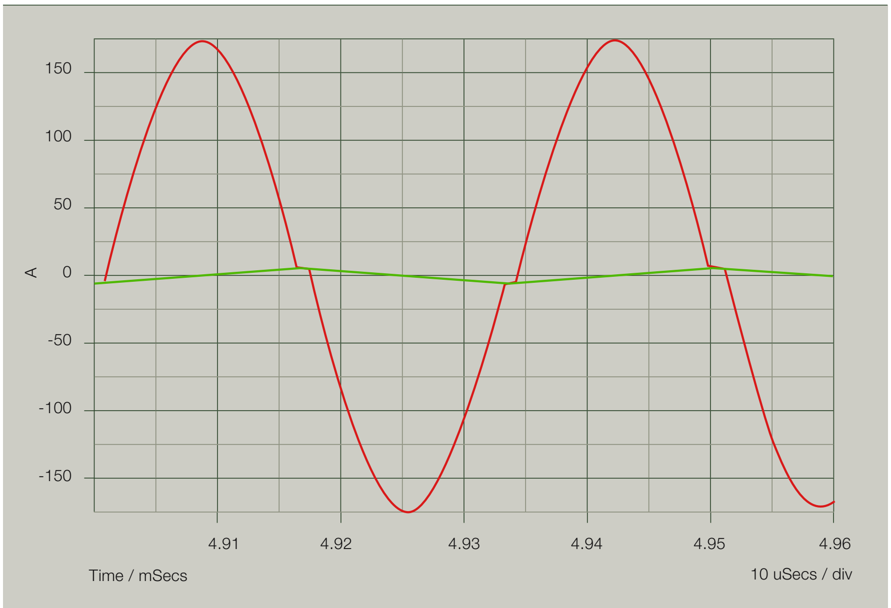


10 Mean losses of resonant converter IGBT per cycle versus resonant tank frequency (due to component tolerances)



The resonant tank circuit is designed so that the devices of the DC/AC three-level front-end converter are operated under ZVS and almost in ZCS due to the very small current needing to be turned off. Actually, the ZVS mode guarantees zero turn-on losses for all of the four active devices, and zero reverse recovery for all the associated free-wheeling diodes. Furthermore, the three-element resonant tank allows the diode bridge rectifier (at the output of the transformer) to be operated under zero-reverse recovery energy, while the low harmonic content resonant tank current allows strong reduction of the passive components losses 11. In summary, all the switching losses of the second converter stage are basically reduced to zero, highly enhancing the overall converter efficiency.

11 Resonant tank current at nominal load



12 The new BORDLINE® M-series

Thanks to the effect of the transformer magnetizing inductance, the converter behavior is insensitive to load or system-parameter variations.

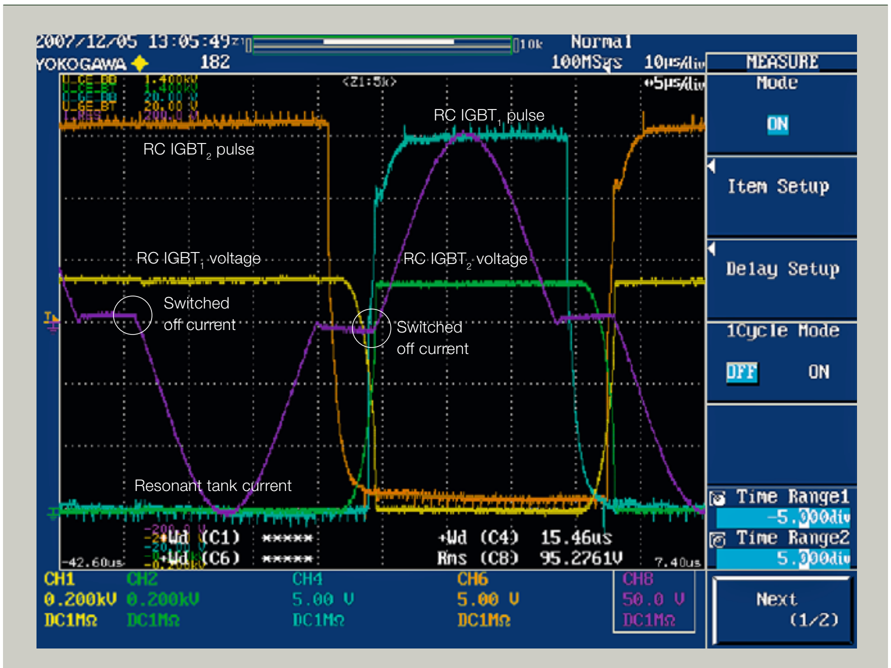
Resonant converter control

With the input converter voltage already stabilized by the input PFC boost stage, the control technique adopted for the resonant stage is quite simple. The converter will in fact always operate in one single point regardless of the line-input voltage variation. Thanks to the function of the transformer's magnetizing current, the converter behavior will be load-independent. Furthermore, the switching functions of the devices of the three-level DC/AC converter in 9 are shifted by 180° by means of the interleaved modulation scheme: The equivalent frequency seen by the resonant tank passive elements is double the switching frequency of the silicon device. In particular, in the BORDLINE M series all the passive elements of the resonant tank are designed for a main frequency of 15 kHz, while the silicon devices are switched at half the value (7.5 kHz) 11.

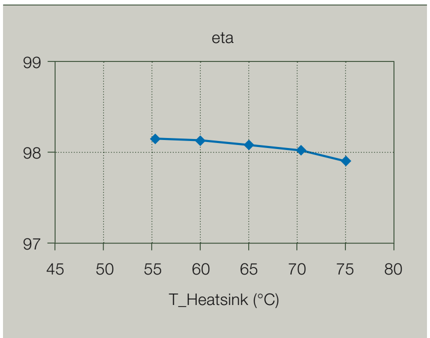
All the switching losses of the second converter stage are basically reduced to zero, highly enhancing the overall converter efficiency.

One of the most important issues related to resonant converters lies in the robustness of the system in the face of variations of parameters of the passive components. It was therefore necessary to evaluate how the con-

13 Resonant stage behavior



14 Resonant converter efficiency for different heatsink operating temperatures



in 13 and 14. In particular, the converter efficiency investigation has been conducted considering several operating points in the whole input voltage range of 700 Vrms to 1,300 Vrms and for different heatsink temperatures.

verter losses were affected by such variations and whether proper ZVS and ZCS could still be guaranteed. 10 shows the diagram of the IGBT's "mean losses per cycle" obtained by simulations using Simetrix®. The diagram shows that fixing, for example, the resonant frequency at 15 kHz (as in this application), it is possible to limit the mean losses per cycle for each IGBT of the resonant DC/DC converter, even if the switching frequency is varied by up to 20 percent from its designed value. In the real world application, switching frequency is stable over time, but the resonant tank frequency may vary due to component tolerances, temperature and aging. Thanks to the effect of the transformer magnetizing inductance, the converter behavior is insensitive to load or system-parameter variations. Problems would have occurred, for example, if the resonant tank would be driven above the resonant frequency. In this case, ZCS operation mode would be lost.

Experimental results

The experimental results obtained during converter tests on the new BORDLINE M series 12 are presented

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References

[1] **Steigerwald, R.** (1988, April). A comparison of half-bridge resonant converter topologies. *IEEE Trans. on Power Electronics 3(2)*, 174–182.

[2] **Sabate, J., Lee, F.** (1991, January). Off-line applications of the fixed-frequency clamped-mode series resonant converter. *IEEE Trans. on Power Electronics, 6*, 39–47.

[3] **Raju, G. and Doradla, S.** (1995, March). An LCL resonant converter with PWM control – analysis, simulation, and implementation. *IEEE Trans. on Power Electronics, 10(2)*, 164–174.

[4] **Nomura, Y.** (2002, May 14). Power supply device for electromotive railcar. U.S. Patent No. 6,388,904 B2.

[5] **Rieux, O., Ladoux, P., Meynard, T.** (1999). Insulated DC to DC ZVS converter with wide input voltage range. *EPE Proceedings*.

Further reading

Lazar, J. F., Martimelli, R. (2001). Steady-state analysis of LLC series resonant converter. *IEEE APEC Rec.*, 728–735.

Yang, B., Lee, R., Chen, et al. (2001). LLC resonant converter for front-end DC/DC converter. *CPES Seminar Rec.*, 44–48.

Canales, F., Barbosa, P., Burdio, J., Lee, F. C. (2000). A zero voltage switching three-level DC/DC converter. *IEEE Intelec Rec.*, 512–517.

Canales, F., Barbosa, P., Aguilar, C., Lee, F. C. (2003, June 15-19). A high-power-density DC/DC converter for high-power distributed power system. *IEEE 34th Annual Power Electronics Specialists Conference*, Acapulco, Mexico, 11–18.

Barbosa, P., Canales, F., Jeon, S.-J., Lee, F. C. (2002). Three-level front-end converter for distributed power systems. *EPE-PEMC Rec*.

Gu, Y., Hang, L., Chen, U., et al. (2005). A simple structure of LLC resonant DC-DC converter for multi-output applications. *20th Annual Meeting of Applied Power Electronics Conference, 3*, 1485–1490.

Coccia, A., Canales, F., Barbosa, P., Ponnaluri, S. (2007). Wide input voltage range compensation in DC/DC resonant architectures for on-board traction power supplies. *EPE 2007*, Aalborg, Denmark.

A turn for the better

New-generation A100 turbochargers for lower engine emissions

Dirk Wunderwald, Tobias Gwehenberger

Although fuel prices have fallen in response to the worldwide economic downturn, this trend is likely to be transitory and will no doubt rise again as the world economy recovers. Of course such a reduction in demand has a positive effect on prolonging the supply of fossil fuels and reducing emissions; however, the broader picture is one of ever increasing fuel consumption and higher emissions.

ABB's new A100 series of turbochargers has been designed to meet future demands for higher compressor pressure ratios and lower engine emissions. This new family of turbochargers provides greater engine power and fuel economy, helping to reduce emissions.

Competition for scarce energy resources, unpredictable fuel costs and stricter emissions legislation are having an important influence on diesel and gas engine development Factbox 1. The impact of these factors, together with continued trends toward higher engine power densities (power per unit volume) and higher power output also influence turbocharger technology Factbox 2.

A turbocharger is a gas compressor driven by the exhaust gases of the engine. It is designed to force air into the air intake manifold, enriching the air content of the air/fuel mix so that fuel burns more efficiently and generates more power.

Stricter emissions legislation and unpredictable fuel costs influence the development of diesel and gas engines.

High compressor pressure ratios[1] are required today not only to increase the power output, historically the main aim of the turbocharger, but also to significantly reduce emissions. They are required to increase the efficiency of, for example, the Miller/Atkinson process[2], which forms the basis of almost all modern diesel and gas engines. In diesel engines the turbocharger helps to reduce NO_x emissions, while in gas engines it is used to shift the point at which knocking begins[3]. Increased pressure ratios, generated by the turbocharger, are also required for engines operating at high altitudes. These compensate for the drop in air pressure at altitude and generally maintain an air intake pressure equal to that experienced at sea-level.

Energy-efficient engines need highly efficient turbocharging systems.

Demand for higher engine power means that increases in effective pressures (ie, the ability of the engine to do work), requires higher turbocharger pressure ratios. However, increasing the turbocharger pressure ratio must be done in tandem with combustion technology optimization. New internal-engine measurements and exhaust after-treatment systems must be considered when developing modern turbocharging systems. In short, if an engine is to be energy-efficient, its turbocharging system also must be highly efficient.

Performance – a crucial factor
During the past decade engine-builders have managed a significant increase in mean engine power output. In the high-speed engine segment, for example, this rise has been about 50 percent, while specific fuel consumption has been cut by approximately 10 percent and engine emissions have been reduced by up to 80 percent 1. Over the same period, taking the compressor power at the engine design stage for the given compressor pressure ratios and flow capacity as a reference, the technical demands made on the thermodynamic and mechanical performance of turbochargers have more than doubled. There is in general an upward trend towards increased mean effective pressures and higher compressor pressure ratios for high-speed diesel and gas engines 2. Furthermore, gas engines typically require higher pressure ratios than diesel engines due to their higher control-related system losses and different fuel management. Full-load pressure ratios of up to 5.8 during continuous operation using aluminum compressor wheels, and high efficiencies, set new benchmarks for power density in turbocharger construction, taking the known limits of single-stage turbocharging a significant step further.

From TPS to A100-M/H turbochargers
Ten years after ABB introduced the TPS series turbochargers, more than 25,000 are operating successfully on small medium-speed diesel engines and large high-speed diesel and gas engines rated from 500 kW to 3,300 kW. While these turbochargers continue to be the preferred choice for engines rated at today's power levels, market demand for engines with ever-higher power levels and

Factbox 1 Environmental impact of engine exhausts

New international regulations, for example in the marine industry and powergen sector, set strict limits for the nitrogen oxides (NO_x) and sulfur oxides (SO_x) emitted by diesel and gas engines and aim to further reduce CO_2 and soot (particulate matter) emissions. Solutions include higher boost pressures, higher efficiency, optimized air-fuel ratios and improved cylinder filling at low loads. All these criteria are supported by the newest ABB turbocharger generations.

Factbox 2 A100-L – the new benchmark for single-stage, 2-stroke turbocharging

To meet the growing performance and emissions requirements of a more environmentally oriented maritime sector, ABB is introducing to this market the biggest and most powerful member of the A100 turbocharger family, the A175-L. The A175-L is the first of the next-generation A100 turbochargers under specific development for low-speed, 2-stroke diesel engines designed for compressor pressure ratios of up to 4.7 at the highest turbocharger efficiencies.

The A100-L program caters especially for advanced two-stroke engine generations planned or under development. ABB currently supplies the 2-stroke engine market with its TPL..-B family of turbochargers, which are used on over 2,600 engines with a total output of more than 60 million kW. ABB remains fully committed to supplying the TPL..-B for present, as well as future 2-stroke engines-requiring compressor pressure ratios of up to 4.2.

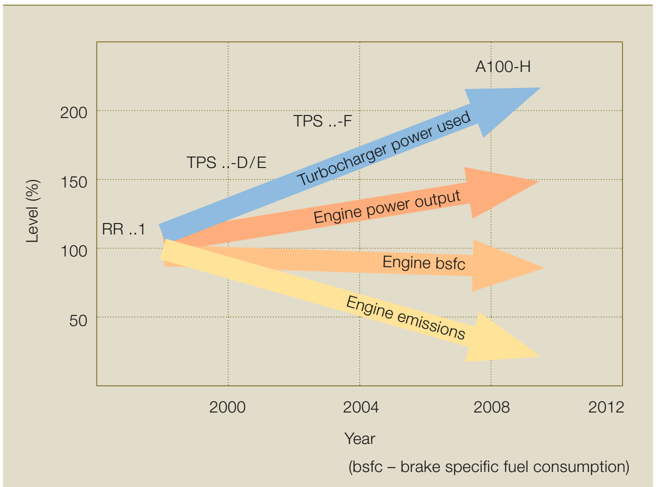
Footnotes

[1] Compressor pressure ratio is the difference between the air pressure in and the air pressure out, and is always greater than 1.0. If the compressor entrance is pt2 and the compressor exit is pt3, then pt3 / pt2 = compressor pressure ratio.

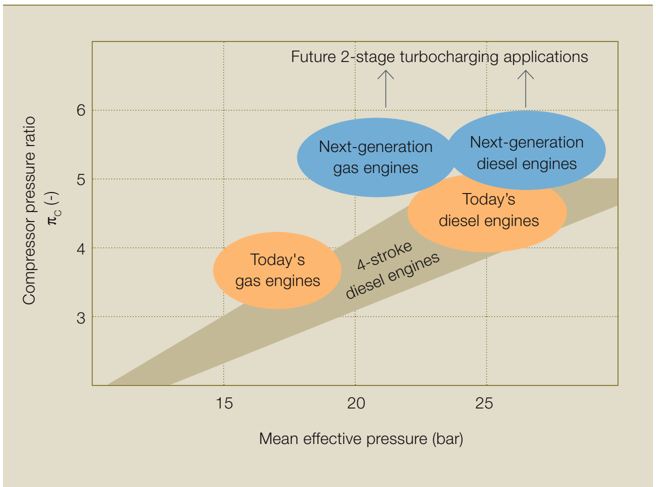
[2] Combustion process innovations to the four-stroke internal combustion engine.

[3] Knocking (also known as pinking or pinging) occurs when combustion of the air/fuel mixture in the cylinder starts off correctly in response to ignition by the spark plug, but one or more pockets of air/fuel mixture explode outside the normal combustion period. The disruption in the precise ignition timing creates a shock wave with a characteristic metallic "pinging" sound.

1 Increasing demands made on turbocharger performance



2 Trends in the turbocharging of modern high-speed engines



efficiencies, together with lower emissions, requires new concepts in engine design and a new generation of turbochargers. It is for these advanced engines that ABB has developed the high-pressure A100-M/H series – the A100-H series for high-speed engines and the A100-M radial turbocharger series for small medium-speed engines 3.

The frame sizes of the A100-M/H series have the same outer dimensions as the field-proven TPS turbochargers. Their oil inlet and outlet ducts are integrated in the foot to match TPS series turbochargers. This ensures that in the case of further development of current TPS-turbocharged engine platforms, these engines can be fitted with A100 radial turbochargers without having to make major changes to the turbocharger mounting. Development of a smaller and a larger A100-H frame size will depend on future market demand.

Design concept

A100 radial turbochargers are of modular construction with a minimized number of component parts designed to match the special requirements of each diesel and gas engine application. Different casing materials are available for different turbine inlet temperatures.

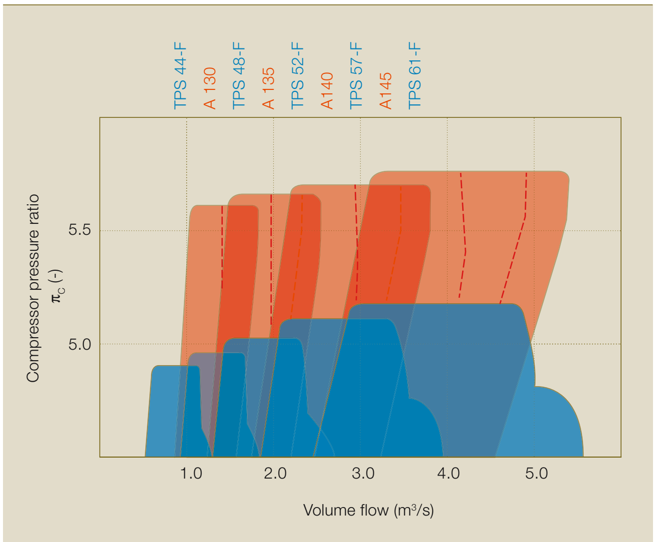
A range of specific design and configuration features enables the A100-M radial turbochargers, for small medium-speed engines, to also be used with heavy fuel oil or with pulse turbocharging systems[4]. Since the exhaust-gas temperatures of these engines are usually lower than those of the high-speed engines, the bearing casings of A100-M turbochargers can be supplied with or without water-cooling.

Aluminum compressor wheels

For the A100 radial turbocharger, ABB developed a cooling technology that allows the continued use of aluminum compressor wheels despite the very high pressure ratios under which they must now operate. This means that cost-intensive titanium components can be avoided, while maintaining the high operational reliability and long

3 New-generation A140 turbocharger

4 Pressure ratio vs volume flow range for A100 turbochargers at full load (for certain specifications even higher values can be achieved)



component exchange intervals users have come to expect from ABB turbochargers.

Cooling with compressor air was shown, by an extensive test program, to be the most efficient and least costly solution for engine builders to implement. The concept is already proven in the field, having been offered for several years as an optional feature for the larger ABB TPL..-C turbochargers.

Turbocharger containment test

The construction of the casing that surrounds the A100 series turbochargers takes full account of the much higher mechanical demands made upon them. During their design, ABB worked closely with engine-builders to ensure optimal mounting of the turbocharger on the engine console and to maintain the compact dimensions of the earlier TPS series. The safety specifications for the turbocharger housing, a vital consideration in view of the significantly increased power density, have been verified both numerically and experimentally using turbocharger containment tests.

In addition to higher casing specifications a stronger shaft to cope with greater power transmission was required. Such a change to the shaft specification meant that a stronger bearing assembly, which was based on the earlier TPS bearing technology, was needed. Furthermore, to retain and ensure safe and efficient turbocharger operation, the A100 series turbines feature a device used successfully in ABB's TPS..-F turbochargers, which maintains turbine centering within the casing.

Cooling technology for the A100 radial turbocharger allows the continued use of aluminum compressor wheels, avoiding the use of costly titanium components.

Thermodynamic performance

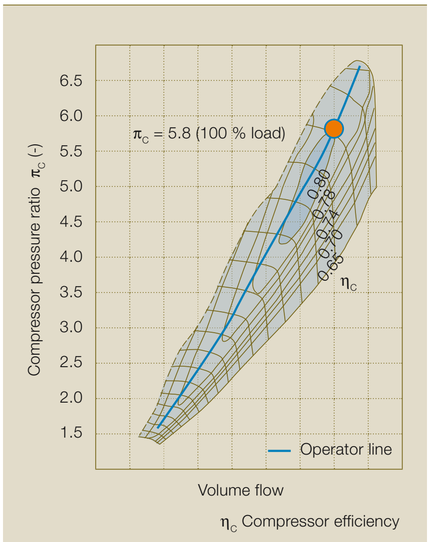
For the new A100-M/H turbochargers ABB has developed three entirely new compressor stages, each with different compressor wheel blading. These provide significantly higher pressure ratios, while maintaining the compressor volume flow range offered by today's TPS..-F turbochargers 4.

The A100 turbocharger features a single-piece aluminum compressor wheel. New high-pressure diffusers[5] and compressor blades were developed in addition to innovative wheel cooling to ensure that the full-load pressure ratios of about 5.8 could be achieved with aluminum wheels. A range of compressor stages is available for every turbocharger frame size, allowing optimal matching to every application. The compressor map in 5, which is based on measurements taken on the recently released A140 turbocharger, shows the high efficiencies, excellent map widths and more than adequate over-speed margins achieved. 80 percent compressor efficiency is achieved on a typical operation line for a full-load pressure ratio of 5.8.

New turbine stages

In addition to the existing TPS mixed-flow turbine stage, a new generation of mixed-flow turbines have been developed for use with the A100 turbochargers.

5 Compressor map (A140-H)

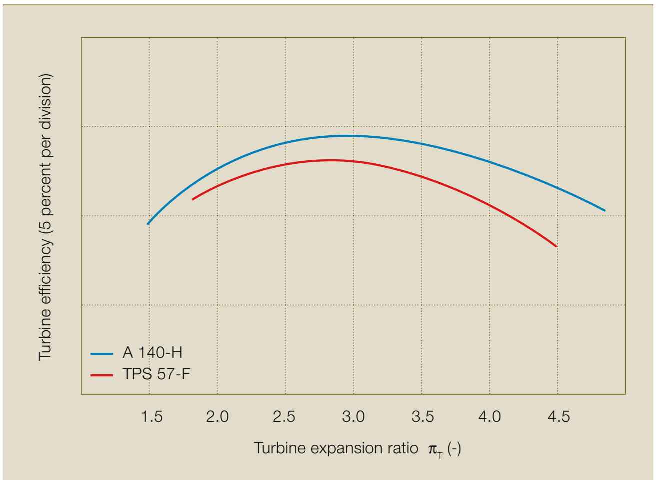


Footnotes

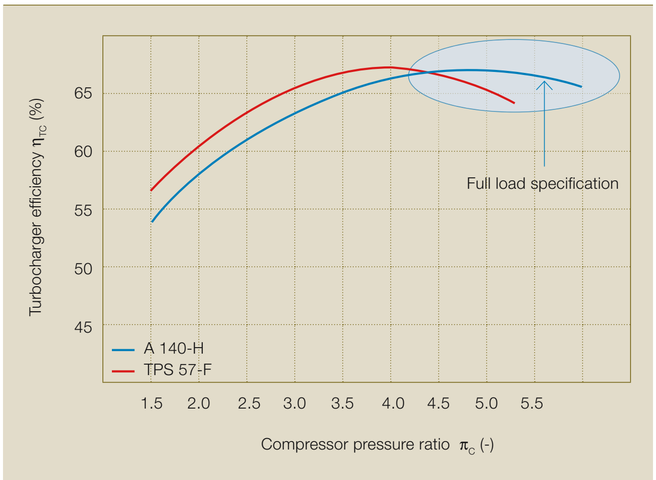
4) In pulse turbocharging, the turbo's turbine inlet is coupled via narrow pipes to certain engine cylinders such that the turbine is subjected to a pulsating flow field synchronized with the opening and closing of the engine valves.

5) The diffuser, located behind the compressor wheel, converts the kinetic energy into static pressure.

6 Turbine efficiencies compared, A140-H and TPS57-F



7 Turbocharger efficiency of A140-H with full-load-optimized specification



A characteristic of this new turbine family is a larger operating range. This allows the high pressure ratio potential of the new compressor stage to be exploited over an even wider range of application. The turbine's design has been optimized for each specific volume flow range, resulting in higher turbine operating efficiencies than the current TPS turbine stages. Flexible seals have been introduced to further reduce flow losses. This has allowed a substantial improvement in turbo charging performance at higher boost pressures 6.

The new-generation A100-series turbochargers represent a quantum leap in turbocharger development for single-stage turbocharging of modern medium- and high-speed engines.

A quantum leap in development

A wide range of available compressor and turbine specifications makes ABB's A100 series of turbochargers ideally suitable for marine, industrial and power generation as well as traction sectors. A comparison between the A100 and TPS family of turbochargers shows the outstanding thermodynamic potential of the new generation turbocharger, in the case of a full-load-optimized turbocharger specification 7. This comparison with TPS turbocharger efficiency illustrates well the performance gained using A100 turbochargers at precisely the range of compressor pressure ratio new engine designs demand. The new generation A100 series turbochargers represent a quantum leap in turbocharger development for single-stage turbocharging of modern medium- and high-speed engines.

Qualification program

The ABB A100 family of turbochargers, like all newly developed turbochargers, was subjected to a mandatory qualification program using combustor test rigs to ensure their reliable operation in future engine applications. The comprehensive series of tests ranged from thermodynamic checks made on new compressor and turbine stages to the mechanical qualification of all newly designed component parts.

The new A100 turbochargers are designed to be operated in high-pressure, continuous-duty applications, at higher speeds than the TPS turbochargers. Extensive shaft motion measurements were performed on the A100 radial bearing assembly at speeds of up to 120 percent overspeed to ensure the rotor dynamics of the new components perform optimally at speeds beyond the current TPS speed range. The combination of the new radial bearing assembly with the new compressor and turbine stages displayed excellent stability characteristics at the required high operating speeds.

Maintenance and service

The maintenance intervals for the A100 turbochargers are similar to those of the TPS family of turbochargers. Although the demands made on thermodynamic and mechanical performance are higher, the new A100 generation of turbochargers will satisfy the requirement for high reliability and low-maintenance operation. A network of 100 ABB service stations around the world provides the necessary service know-how and logistical support to satisfy the needs of customers. Customers using advanced diesel and gas engines fitted with A100 series turbochargers can rely on ABB's customary delivery of high standards in performance and maintenance of this new generation of turbochargers.

Introduction program and early results

In mid-2007 the first A140 prototypes were successfully commissioned on ABB test rigs. The rigorous examination program was successfully completed for this first frame size of the new turbocharger series and has been released for series production Factbox 3. ABB is currently introducing further sizes of the A100-M/H turbocharger to the marketplace.

In the run-up to the introduction of the A100 series, engine test rig trials were carried out to verify the thermodynamic performance. The high pressure ratios and efficiencies that can be achieved with the A100 series clearly demonstrate that these turbochargers can accommodate the high power densities expected for future engine requirements. Hundreds of hours of continuous operation on the test rig have also confirmed the high performance level of the A100 series. These new generation turbochargers are currently under trial at selected field installations. Successful engine trials of further frame sizes are already under way.

Factbox 3 The A140-H turbocharger

At Luttelgeest in the Netherlands, power generators, in a combined heat and power plant used to heat large greenhouses, have been fitted with A140-H turbochargers. Here the CO_2 produced by the generators is used to increase plant growth.

A140-H turbochargers run on power generators in large greenhouses at Luttelgeest in the Netherlands.

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Practicing what we preach

ABB promotes the use of robots in manufacturing and uses them to manufacture ABB products

Åsa Rylander, David Marshall

Robots have made a major impact on the productivity and safety of manufacturing industries. They are primarily used for material handling, moving products around the factory safely, but also offer reliability, tirelessly carrying out highly repetitive tasks, sometimes in hazardous environments, increasing safety in the work place.

ABB is a leading manufacturer of industrial robots and has played a significant role in promoting their use in industry. In fact ABB not only recommends their use to customers, but also use them to improve the efficiency of ABB's production lines.

Producing efficient products using highly efficient production methods remains a strong focus for ABB. ABB's Low Voltage (LV) Motors factory in Västerås, Sweden has not only optimized its production through the use of ABB robots, but has also recently developed and launched, in 2008, a new generation of highly efficient motors.

ABB has been producing LV motors at Västerås, Sweden since 1947. Large black and white photos, taken over 50 years ago, line the walls of a corridor at the factory showing dozens of busy men and women hand assembling motors. Today, 19 robots keep the ABB LV Motors factory competitive despite the emergence of rival companies in low-cost countries. The factory employs 210 personnel and produces 100,000 LV motors per year. A two-pronged strategy was adopted by ABB to remain competitive. ABB not only focused on product development, launching new innovative generations of highly efficient motors, but also focused on the efficient manufacture of its product.

Improved cycle times of as little as 80 seconds for the assembly of small motors have contributed to the success of ABB's Västerås motors factory.

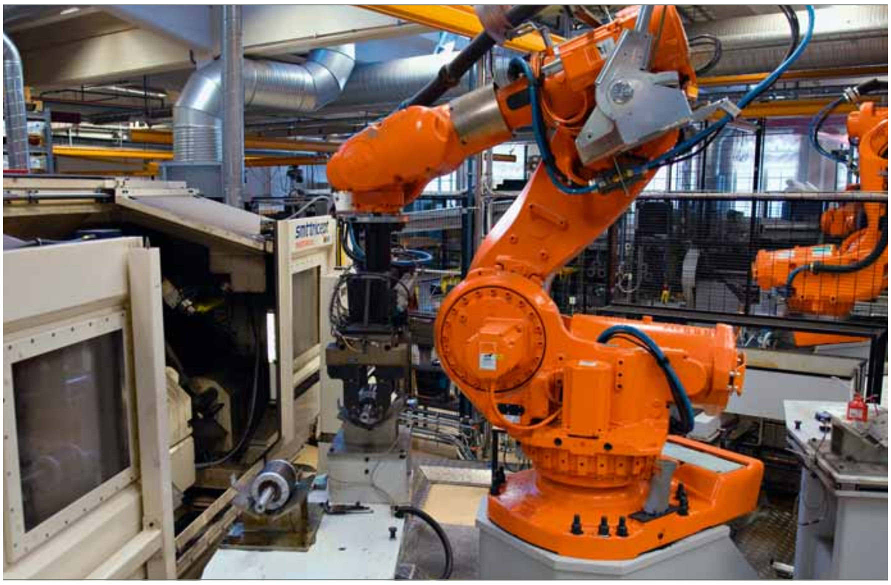
By automating the production process fewer people were required, reducing production costs and associated expenses that result from fluctuations in demand. ABB has many years of experience in the automation business and is particularly well equipped to automate production processes. The application of ABB robots to the production of motors ranging from units weighing 500 kg down to units weighing just 30 kg, has reduced production cycle times. The cycle time for the assembly of small motors, for example, is now only 80 seconds. Improved cycle times and reductions in personnel have contributed to the success of the Västerås motors factory. Six robots on the assembly line, for example, allowed 30 percent savings in personnel.

The first ABB robot was an IRB 6, installed in the foundry of the factory in 1974, and since then a wide range of robots have been installed[1)]. For the most part these robots have been employed to transport materials, but have also been used to automate most of the production processes, including welding, casting, pressing, winding, assembling and packaging 1 2. Since their introduction, much of the heavy lifting, previously carried out either manually or by cranes, is now done by robots, helping to reduce the risks of injury to workers on the production line 3. The ABB LV Motors factory in Västerås is now one of the most modern ABB motor manufacturing facilities.

Of course automation is not the only important focus of attention required for a LV motors factory to remain competitive. The products must remain innovative and competitive. Motors are used in just about every industry, for example to power pumps, compressors, fans, cranes, paper mills and many other machines. About 65 percent of electricity is consumed by electric motors in industry, so huge savings in carbon emissions and wasted power could be made by relatively small improvements in the efficiency of motors. Efficiency is a measure of how well a motor converts electrical energy to useful work.

While the ABB Motors product catalogue rates the efficiency of different motors at about 95 percent, this still means that 5 percent of the electricity gets wasted in terms of dissipated

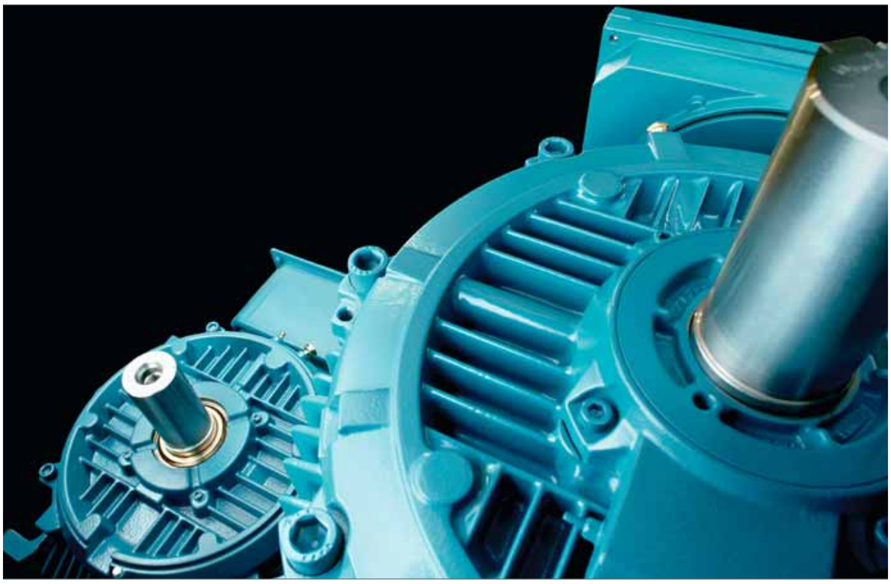
1 Winding by an IRB 7600



2 Packaging by an IRB 6400

3 Heavy lifting by an IRB 6600

4 M3BP type motors



heat. To address this problem ABB LV Motors have developed a new motor generation. For the new M3BP motor type, the losses have been reduced by about 5 percent compared to those of the older generation motor series 4.

If the production of the new series of motors replaces the older generation motors in terms of the volume produced at the factory, the yearly carbon dioxide emissions reduction would be equivalent to the emissions from 90,000 cars.

Nineteen orange robots keep the ABB LV Motors factory competitive despite the emergence of rival companies in low-cost countries.

The new product portfolio also includes a premium range, M4BP-type motor, with 10 percent lower energy losses than the M3BP-type motors. If this range is adopted by industry, further reductions in forecast carbon emissions can be expected. Although carbon emissions do have an economic impact on industry the most attractive incentive to use this new generation of motors will be to reduce energy costs.

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Footnote

[1] Three ABB IRB 4400 robots, 10 IRB 6400 robots, three IRB 7600 robots, one IRB 6000 robot, one IRB 60 robot and most recently in 2008, one IRB 6600 robot have been installed at the LV Motors factory in Västerås.

Every bit counts

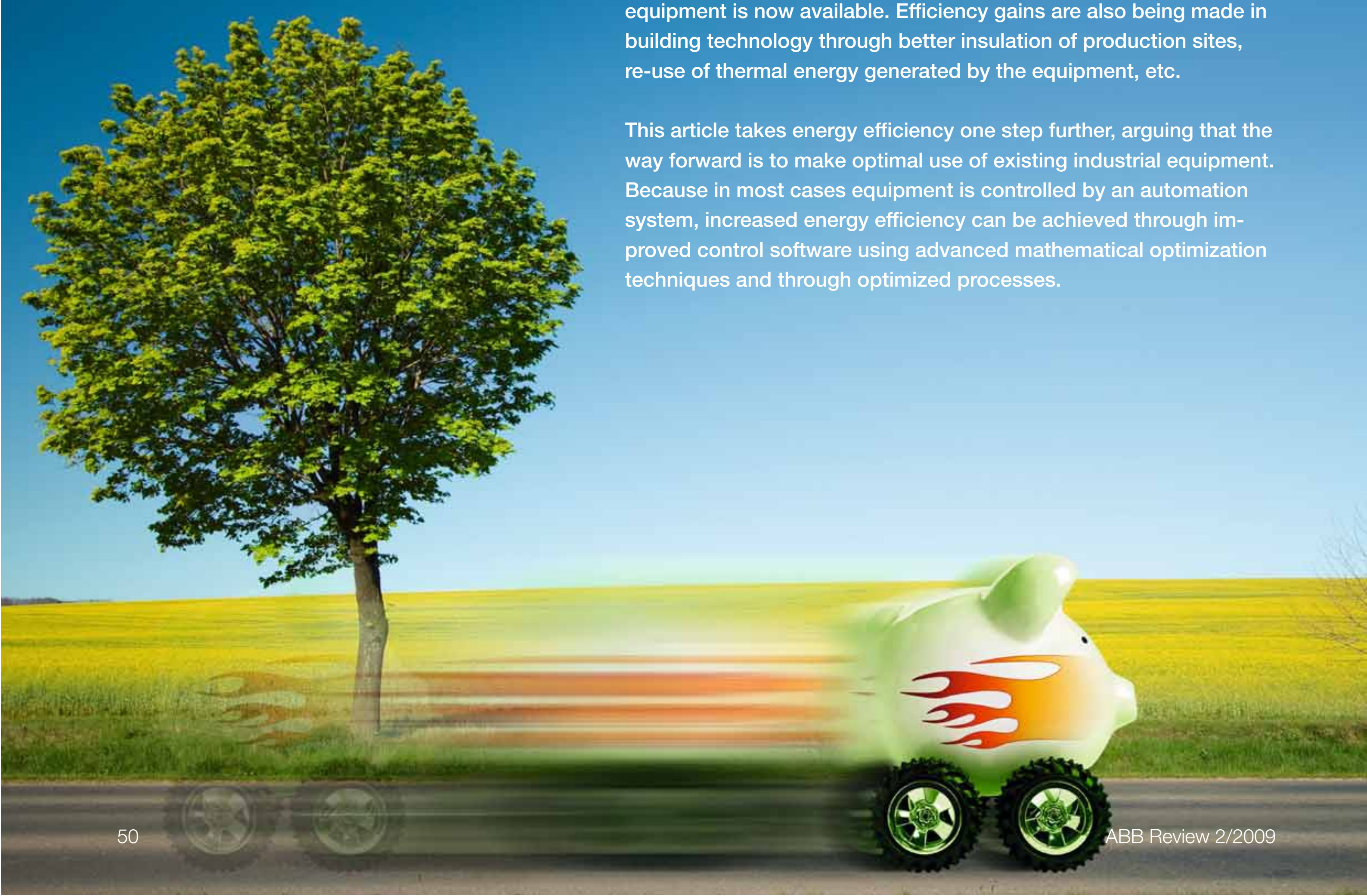
Improved control software and optimized processes are contributing to increased energy efficiency

Christopher Ganz, Alf Isaksson, Alexander Horch

Renewables, nuclear power, clean coal – these are among a long list of buzzwords being used to address the future of energy. In the global struggle to match demand with supply, these are only one part of the equation. Increasing the supply inevitably requires resources of some kind, whereas reducing the demand results in a reduction of resource consumption. For decades, environmental organizations have sought to limit the use of energy. In the past, this implied reducing the standard of living – ie, doing less of the same.

A far more convincing idea is doing the same with less – increasing efficiency by applying more efficient technologies. One well-known example is the replacement of incandescent light bulbs with compact fluorescent bulbs or LED lights. And in industry, highly efficient equipment is now available. Efficiency gains are also being made in building technology through better insulation of production sites, re-use of thermal energy generated by the equipment, etc.

This article takes energy efficiency one step further, arguing that the way forward is to make optimal use of existing industrial equipment. Because in most cases equipment is controlled by an automation system, increased energy efficiency can be achieved through improved control software using advanced mathematical optimization techniques and through optimized processes.



To understand what is meant by running a plant with optimized software and processes, one simply needs to think about driving a car. It is highly plausible that a car driven by two different people under the same conditions will not consume the same amount of energy. Why? Because driving techniques differ. In a plant, it is the operation and strategy that governs the actual energy consumption.

The strategies for energy-efficient plant operation are much like those required for energy-efficient driving:
Stop the motor at red lights Produce products according to specs and run the plant only at capacity.
Shift gears early Be open to change.
Keep the appropriate pressure in the tires Run an optimally maintained plant.
Do not accelerate when approaching red lights Run the production predictively in accordance with maintenance and production schedules.

If these strategies are applied properly, there is no need to "slow down" to save on fuel consumption. Experiences from modern eco-drive trainings exemplify this: It is possible to drive faster while consuming less fuel. In a modern, much more complex plant, the lesson is the same: Running a plant optimally leads to greater energy efficiency.

This article focuses on the different levels of the automation hierarchy. The various functions available in an automation system can be improved to make a controlled process more energy efficient. Functions varying in scope (from individual devices to those covering the whole plant) and time horizon (optimization within milliseconds up to the life cycle of a plant) can all have an effect on the plant's efficiency. The following three areas are addressed here:
Advanced control Today's advanced controllers have the ability to solve an optimization problem in every step, and can therefore have minimum energy as one of the target functions or boundary conditions.
Production planning and scheduling Proper planning and optimized scheduling of a plant can reduce waste in terms of time and material, which results in doing more with the same energy.
Monitoring To detect whether a plant is running at its peak efficiency, it must be monitored closely to identify any abnormal behavior that may result in increased energy consumption.

Better control, less energy

Many people may not immediately connect improved control with energy savings, but rather with improved product quality, increased production and reduced chemical addition. But regardless of the intended target for the control, a positive side effect is almost always a reduction in energy usage, or that more product is produced using the same amount of energy as before.

The various functions available in an automation system can be improved to make a controlled process more energy efficient.

Just by retuning the basic level-one PID control loops, energy consumption may be significantly impacted. Even though the savings for a single loop may be small, the sheer number of loops (hundreds if not thousands for a large process-industry plant) most often makes the total savings significant.

Sometimes an advanced control or optimization solution targets the energy more directly. Some successful examples where significant energy savings have been verified follow.

Power generation

A good place to start saving energy is of course at the source – ie, where the energy is produced.

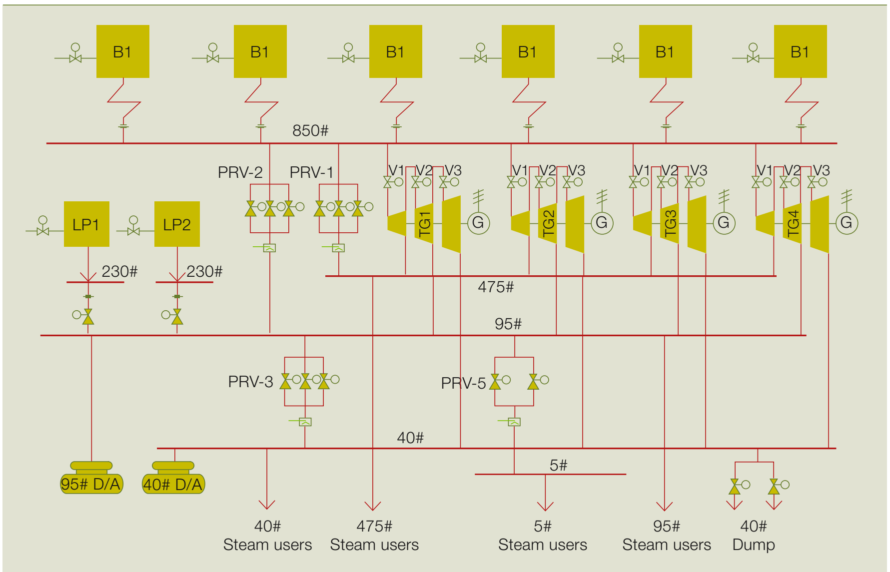
Cogeneration of steam and power

At Point Comfort (in Texas, USA), Alcoa Inc runs a large refinery where bauxite is converted to alumina 1. Since this is a very energy-consuming process, Point Comfort utilizes its own powerhouse with multiple boilers, turbines and steam headers. Most of the energy needed is produced in-house, but electricity is also purchased from the local power grid.

With varying prices of electricity and fuel (ie, natural gas) the first challenge is to determine the optimal mix of in-house versus purchased energy. This is now done by solving a mixed-integer linear program every 15 minutes using the current fuel and electricity prices, which are downloaded from the Internet.

The results from the steady-state optimization are fed to a model-predictive controller (MPC), which runs with a

1 A graphical overview of the Alcoa Point Comfort Power Plant



much faster cycle (< 10 s). The MPC is based on an empirical linear dynamic model, and delivers 28 manipulated control set points.

ABB commissioned this system in 2005 and it immediately led to greatly improved process stability; for example, an 80 percent reduction of steam pressure standard deviation was achieved. A 1 percent savings in overall energy cost was verified, giving the customer six months payback time. A more detailed presentation of the system and the solution can be found in [1].

A novel technique to measure the steam temperature inside the refiner is being used in TMP mills for feedback control.

Power generation: power boiler startup

Another example of energy savings is the optimal startup of fossil-fuelled steam power plants. In the deregulated power market, these power plants are used for more than just base load, and hence encounter many more stops and starts. The startup time for a boiler is highly constrained by thermal stresses; ie, too-high temperature gradients in thick-walled parts of the boiler and turbine may lead to cracks in the material.

Given a model and online measurements, it is possible to calculate the actual thermal stress. Thus a boiler model – which was not allowed to violate the constraint on thermal stress – was developed and used to optimally manipulate the fuel flow rate and high-pressure (HP) bypass valve position.

ABB has installed this technology at seven power plants, with three more installation projects underway 2. The typical fuel savings for a single startup is between 10 and 20 percent. With 50 to 150 startups per year, this corresponds to 0.8 to 8 million kWh per installation. For more details on this application, see [2].

Control of TMP refiners

A more typical control problem is of course at the consumer's end. An example of a very energy-intensive process is the production of thermo-mechanical pulp (TMP). A mix of wood chips and water are ground in a narrow gap (< 1 mm) between two disks, where either one or both may be rotating. The rotors are driven by large electrical machines; for a modern TMP refiner, a 30 MW motor is not unusual.

Much of the electrical power goes into producing steam in the refining zone, and a lesser part into the mechanical work on the wood. Now a novel technique to measure the steam temperature inside the refiner is being used in TMP mills for feedback control 3.

Verified results at the Hallsta Paper Mill, belonging to Holmen Paper in Sweden, show direct energy savings of $7 to $13 per metric ton of produced pulp with improved pulp quality. For a TMP line with an annual production of 100,000 tons, the total savings is then $700,000 to $1.3 million per year (note that mills usually have more than one line). Add to this indirect savings from fewer production stops for the TMP line and fewer sheet breaks on the paper machines, and the annual savings may be more than $2 million for one TMP line.

More production – less energy

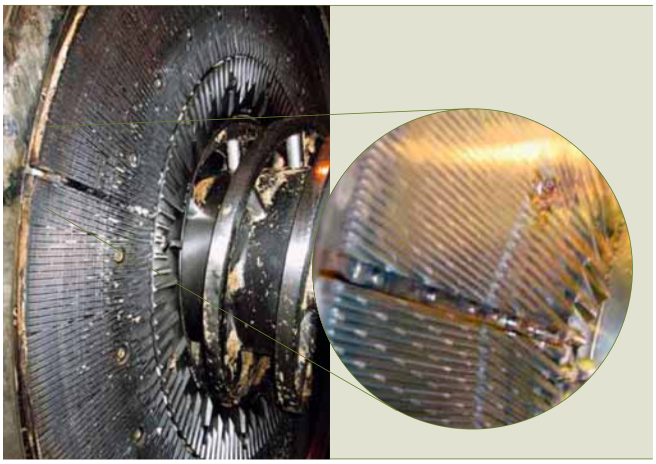
Any plant operation that does not produce quality-as-planned product obviously wastes energy. Therefore, startup times, quality changes and the duration of plant upsets need to be minimized. While these are not new solutions, they have been difficult to manage. Now, with modern optimization methods, it is possible to actually reach optimal operation.

An innovative ABB software solution – quality-based retrim optimization – computes the optimal cutting pattern based on actual quality data.

Plant operation and scheduling strategies are often based on heuristics and experience. This in itself is not a disadvantage but it does hinder the transition toward a truly optimized pro-

2 The Weiher III power plant, location of the first boiler startup installation

3 The stator grinding segments with a close-up of the temperature sensor array used in producing thermo-mechanical pulp (TMP)



duction, with respect to both optimization and scheduling.

The optimal management of plant assets also implies that those assets are at their optimal condition for production. Non-optimal production is often caused by non-optimally working assets, resulting in quality or yield reduction.

Finally, production scheduling is a key for energy-efficient production. The smooth (and truly optimal) use of production assets prevents the use of too much energy at one time whilst wasting it at other times. For instance, plant actuators require energy (eg, pumps, heating, cooling). Any avoidable variance in such process variables immediately implies avoidable variances in manipulated variables.

Paper retrimming optimization

Consider the case of paper production where a predefined cutting pattern has been optimally computed based on customer orders. Due to variation in production, the predefined cutting pattern typically proves to be suboptimal given the actual quality of the jumbo paper reel. This results not only in increased waste paper that needs to be recycled, but also in loss of profit.

An innovative ABB software solution – quality-based retrim optimization – computes the optimal cutting pattern based on actual quality data 4. The underlying patented method is able to solve the extremely complex optimization problem in just seconds. In so doing, more good-quality paper results from each jumbo paper roll, thus decreasing the amount of paper that must be reproduced. Based on the energy consumption per ton of produced paper, a savings of just a fraction of the recycled paper is significant. Assuming an annual production of 400,000 metric tons, preventing just 1 percent of the final paper from being recycled can result in a savings of 10,000 MWh of energy (both electricity and gas).

Coordinated production scheduling

Melt-shop scheduling in steel production is a difficult problem since the amount of different materials and orders is very high. ABB has developed a solution that is able to simplify and solve this complex problem in an optimal way.

> Today's automation systems already collect a vast number of data points that can reveal a lot about a plant.

The same solution applies to the next step in steel production – the hot rolling mill 5. Scheduling of hot-rolling production is not as complex as melt-shop scheduling, but still presents significant challenges.

Having solved those two scheduling solutions, considerable energy savings lies in the coordination of both schedules in order to use both production plants optimally and to minimize the residence time of each freshly casted steel slab in the slab yard. This is important since slabs need to be hot before entering the hot rolling mill. The energy required to heat each slab, which is about 1,000 m^3, is 10,000 kW. If one out of 10 slabs can be hot charged, ie, fed directly from the caster into the hot-rolling mill (thus avoiding reheating), a typical mill could save 21,000 tons of CO_2 or, in financial terms, \$3.9 million per year.

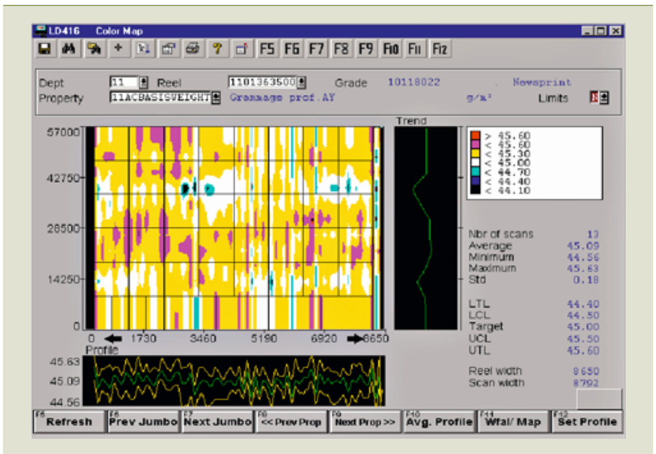
Manually, these scheduling problems cannot be solved. But modern optimization software can now deliver such results, allowing operators and planners to monitor and – if required – change schedules.

Monitoring energy-wasting equipment

Even if plant controllers, planning and scheduling are optimized to perfection, it is clear that over time the performance will deteriorate due to plant aging and process failures. In the case where some equipment breaks, this might be obvious; in many cases, however, deterioration is gradual, or cannot easily be located in the process by relying on traditional operator tools such as process displays, trend curves and alarm lists. But even if not recognizable by even a skilled operator, abnormal process behavior leaves its traces in the measurements collected within the plant.

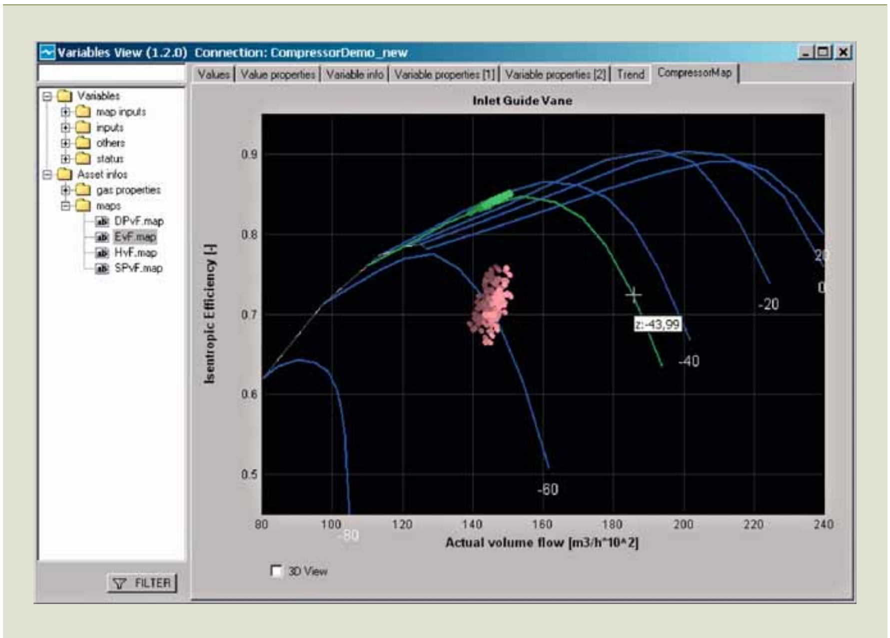
Taking an in-depth look at these measurements using advanced signal-

4 Two-dimensional quality data from paper production



5 Hot-rolling mill in a steel plant. Slabs coming from the melt shop are being rolled into coils.

6 Compressor map derived from drive signals



analysis algorithms may reveal the behavior more clearly. Some key performance indicators (KPIs) are easily calculated from measurements collected in the distributed control system (DCS). Differences in temperature, together with a flow measurement, can in some cases provide quite a good indication of the energy consumed. Comparing this calculation with a "clean" measurement that was taken when the plant was evidentially operating close to the design (ie, early in its operation or after an overhaul), a degradation in efficiency can be easily detected. To then diagnose the cause of the degradation often requires either an experienced maintenance engineer, or yet another set of algorithms.

More complex monitoring systems not only apply simple calculations to come up with performance indicators, but they also apply more advanced plant models where parameters are identified, so the model matches the plant (degrading) performance. These parameters then give a better view of the internal behavior of the system than the measurements available in the DCS.

Monitoring process equipment through electric drive data

A common conclusion when introducing advanced monitoring is to introduce more sensing equipment – after all, obtaining more information about a process does require more measurements. However, what is very often forgotten is the fact that today's automation systems already collect a vast number of data points that can reveal a lot about a plant. Even in places that are not obvious, data is collected and continuously analyzed.

> Even if not recognizable by even a skilled operator, abnormal process behavior leaves its traces in the measurements collected within the plant.

One example is the drive system. Apart from the algorithms that control the system, it contains a data collector that is normally used to diagnose the drive's behavior. However, the data contained therein does tell a lot about the process that is finally controlled by the motor. By matching the drive system's signal patterns with the observed behavior of the process or by tuning process models to correspond to the observed signals, information about the controlled process can be retrieved by means of signals that are already in the system, without introducing new (and costly) measurements. 6 shows the diagnosis of a compressor by analyzing the signals in the drive system.

A holistic view matters

In addition to the technical complexity of energy savings through optimization, there is also an operational complexity. Modern optimization solvers enable fast and reliable solutions to complex technical problems. Another equally important challenge is to integrate computer-based production scheduling and plant operation into plant work processes.

The buy-in of the production planning and plant operation teams is essential for successful modern plant optimization. Knowing that, topics like usability, maintainability, modularity and proper training will become central concerns for both vendors and users. If these issues are treated comprehensively, production success and energy savings will not be contradictory.

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References

[1] **Valdez, G., Sandberg, D.G., Immonen, P., Matsko, T.** (2008, November). Coordinated control and optimization of a complex industrial power plant. *Power Engineering Magazine, 112*, 124–134.

[2] **Franke, R., Weidmann, B.** Starting the boiler: Startup optimization for steam boilers in E.ON power plants. *ABB Review* 1/2008, 57–62.

Intelligent in-house service

Hotel guests can now enjoy increased comfort with fewer energy requirements thanks to ABB's i-bus® KNX building control system

Wang Dajiang

Whether through experience or stories related by friends and family, how many of us have spent time trying to adjust air-conditioning systems in hotels to avoid fridge-like temperatures, or were defeated by lighting, shutters or blinds that seemed to have a mind of their own! While guests were fighting their own battles, many hotels had to deal with high energy costs.

Thanks to ABB's i-bus KNX intelligent installation system, hotel guests can now enjoy even greater comfort with minimum effort. While comfort is enhanced, these "intelligent" hotels are benefitting significantly from reduced energy requirements and improved efficiency, which directly translate into increased savings.

Sustainable results

For many travelers, hotels have almost become a home away from home. As in their homes, guests want to feel safe and comfortable, and hotels have always strived to provide such an environment. However, in many cases this has proved costly and inefficient in terms of energy usage.

In recent years, innovative solutions and products allowing various home electrical systems to be flexibly connected and easily – but intelligently – controlled via the existing electrical network have started to appear on the market. Functions provided by such a system allow atmospheric lighting, heating and ventilation, the monitoring of windows and doors, and shutters and blinds to be controlled. One such system, the i-bus® KNX intelligent building control system from Busch-Jaeger, an ABB company, allows multiple electrical devices to interact wherever and whenever the user requires [1]. As well as its application in residential buildings, ABB's i-bus KNX control system is now widely used in public buildings, such as museums, airports, office buildings and hotels.

The i-bus KNX intelligent installation system is based on the proven KNX technology, which is now accepted as the world's first open standard, ISO/IEC14543, for device control in industrial, commercial or residential buildings. In July 2007, the KNX standard was accepted as the Chinese National Standard, GB/Z 20965-2007, which is titled "The control network home and building electronic system (HBES) technical standard."

The use of the i-bus intelligent control systems in top grade hotels has not only improved the quality of the service in terms of comfort and convenience, but the all-important energy-saving goal has been realized through the automatic and intelligent control of lighting, curtains and blinds, the air-conditioning system and TV.

Welcome to another world

Intelligent service using ABB's i-bus system begins the moment a guest enters the hotel. In the lobby and public area, the air conditioning and lighting are automatically controlled to provide the required illumination and temperature. Using natural light as a reference, a brightness sensor determines if, and to what level, lights should be turned on to maintain a constant illumination. Illumination and temperature settings vary throughout the day. The curtains in the lobby are also controlled using a light sensor.

The i-bus control system adjusts itself to match the varying flow of people in public areas during the day. Motion detectors control the amount of lighting provided depending on the amount of activity they register. During busy periods, most or all of the lights are switched on and the air conditioning is optimally set. As the flow of people decreases, part of the lighting and air conditioning is switched off. And at night when activity is most probably at its lowest rate, the lighting and air conditioning are controlled only by the motion detector to keep energy consumption low.

> The i-bus® KNX intelligent installation system is based on KNX technology, which is now accepted as the world's first open standard for device control in industrial, commercial or residential buildings.

Intelligent rooms

Once the hotel guest inserts a special card into the slot provided in the room, the ABB i-bus system sets the lighting to welcome mode and the air conditioning system to comfort mode (ie, 23 °C in summer and 28 °C in winter). Dimming the reading lamp, adjusting the electric curtain and other operations can be carried out by the guest from the comfort of their bed 1.

The air conditioning system is automatically controlled via an i-bus thermostat. To maintain the required temperature setting, the wind speed automatically switches from high to low before finally stopping. Air conditioning control is interlocked with the opening and closing of doors and windows, and so when a window or balcony door is open, the air conditioner turns off automatically.

Before going to sleep, the guest can turn off all lights via a switch located over the night table, and the air conditioning system will then automatically switch to night mode 2. A night-activity mode button turns on a night light and a light in the bathroom if required. After the card has been removed from its slot as the guest leaves the room, all lights are turned off and the air conditioner is automatically switched to vacant mode (ie, 30 °C in summer and 18°C in winter).

Improved housekeeping

The ABB i-bus system has also helped to increase housekeeping efficiency. All information concerning room vacancies and service or emergency calls is displayed on a computer in the housekeeping department. This information is gathered using switch sensors in a guest room, which transmit various instructions over the i-bus system to the housekeeping computer. Device control in each room is interlocked with the housekeeping computers at the reception desk. This allows the lighting and air conditioning in the room to be automatically turned on once a guest has checked in and turned off immediately following check out. In this way energy is saved without inconveniencing the guest.

Outside lighting effects

Depending on what is on, lighting control in scenic areas and in the parking lot is achieved using a combination of integral, division and individual control. In general integral control is implemented in most scenic areas and in the parking lot. This means a timer controls when the lights are turned on and off, while light intensity is sensor controlled. In spring, a timer is also used for irrigation, and is set according to climatic and soil conditions. During festivals or large events, the lights in all scenic and garden areas are controlled via the computer in the central control room. In the parking lot, the lighting in different sections can be individually controlled via a panel in the control

Sustainable results

1 Operations such as adjusting the electric curtain can be carried out from the comfort of the bed.

2 All lights can be turned off via a switch located over the night table. The air-conditioning system will then automatically switch to night mode.

room. In addition, ventilation fans can be turned on and off at set times.

Top-quality service in Beijing

The Changbaishan International Hotel in Beijing is located close to the Olympic stadium (ie, Bird's Nest) and swimming pool (ie, Water Cube), and is situated in the center of the Olympic business zone. This five-star luxury hotel uses ABB's i-bus intelligent system to control lighting and air conditioning in its 220 uxury guest rooms, lobby, multifunction hall, business center, gymnasium, hallway and other public areas.

The conventional switches[1)] in each guest room are user-friendly, and extra low-voltage wire is used to connect them directly to the i-bus system. Intelligent control, which is easily realized, achieves comfortable and convenient reading, rest and TV modes. By pressing a particular switch over the night table, guests initiate the service-call function. The relevant signal is displayed on a display outside the room door, as well as on computers in the floor service room and housekeeping department, thus minimizing the service response time.

There are three different visualization interfaces: one each for the reception, and the maintenance and housekeeping departments. In addition to the basic functions, an automation function, which is connected to the hotel management system, enables the room to be managed and prepared efficiently. For instance, when a guest checks out, the room is automatically set to stand-by mode. At all times the status of each individual room in terms of temperature, occupancy, service calls, curtains, lighting, etc is graphically displayed at the operation desk.

Remarkable savings

ABB's i-bus intelligent control system doesn't just improve the already high level of service offered in many hotels, it also allows them to achieve significant energy savings.

Operational efficiency can be increased by both regular maintenance and system optimization. When it comes to saving energy in a central air-conditioning system, decreasing consumption in components such as the chiller, water pump and room electrical devices (eg, the fan coil unit) helps meet the energy-saving goal.

Through proper control of the electrical devices in a room[2)], the energy consumed and the total load on the air conditioning system are greatly reduced. In turn, the energy consumed by the cooling water units, the three-speed fans or boilers is minimized. To be more specific, a one degree increase in summer or a one degree decrease in winter in a typical room temperature setting results in a 6 percent reduction in energy consumption by an integral air-conditioning system [2]. In other words, the automatic adjustment of room temperature settings via an intelligent thermostat achieves the all-important energy saving goal.

The annual energy consumption bill in Beijing's Changbaishan International Hotel before ABB's i-bus intelligent control system was installed was around $702,000. Now the hotel estimates it can reduce the cost of running the central air-conditioning system per year by an average of $84,200! This figure is calculated on the basis that over a 24-hour period, the 220 rooms will operate for eight hours in energy-saving mode, another eight in night mode and the remainder in normal mode.

It cost $322,000 to install the system in Beijing's Changbaishan International Hotel. With annual savings estimated at $84,200, the calculated payback time of the system works out at less than four years. Most definitely money well spent.

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References

[1] **Doerstal, B.** Value-added comfort: Intelligent electrical installation technology makes living safer, life easier and the use of energy more efficient. *ABB Review* 2/2008, 10–14.

[2] **Bin, Y., Baoyi, G., Xiaoping, M.** (1999). Optimization of indoor design parameters of comfort air conditioning. *Heating and ventilation air conditioning*, *29* (1), 44–45.

Footnotes

1) The style and color of the switches are in harmony with their installation environment.

2) This can be achieved by switching to the "off" or "energy saving" mode when the room is vacant, to the "energy saving" mode when the guest is out, and to "night" mode when the guest is sleeping.

Metamorphosis

Adapting rapidly to change using the IDEAL improvement model

Aldo Dagnino, Andrew Cordes, Karen Smiley

Corporations must adapt rapidly to changing markets and adopt new technologies to remain competitive. Such adaptations are particularly important in a rapidly changing economic climate. Flexibility and a willingness to change are important qualities that must be fostered and encouraged, at all levels, if businesses are to respond effectively to shifts in product demands or to altered customer requirements. To encourage a positive environment for such change, the process for change must be carefully planned, well managed, properly justified and applied with sensitivity. ABB uses the IDEAL^{SM} 1.0 model as a framework to guide improvement processes so that effective changes are deployed efficiently.

ABB provides its business units (BUs) with innovative solutions to improve the introduction of new products, new technologies, new methodologies, and innovative processes that enhance ABB's products or methods of production. This assistance helps ABB's BUs to provide novel products and services to their customers and to enhance ABB's competitive position.

Developing new products or introducing new technologies, methods, or any kind of improvements to the BUs are exciting activities that provide many benefits. However, such activities can be disruptive and trigger resistance to change at different levels within the organization. It is important, then, to have a systematic approach to manage a change or improvement program. All of ABB's research centers are concerned with bringing change in one way or another to ABB. Improvement programs directly affect BUs and typically involve collaboration to introduce new technologies, develop new products, use new materials, improve production methods, enhance the design of existing products, optimize product development methods and promote many other initiatives. ABB Corporate Research effectively uses an organizational improvement model to collaboratively establish, execute, and accelerate improvement programs in BUs. This model, called IDEAL℠ 1.0, was first developed by the Carnegie Mellon® Software Engineering Institute (SEI) and its original aim was to improve software development processes. Nevertheless, ABB has successfully employed IDEAL to guide other activities that will also create improvements within the company's BUs.

Phases of the IDEAL model

The IDEAL 1.0 model is defined by five main phases [1] 1:

1) Initiate
2) Diagnose
3) Establish
4) Act
5) Leverage

Each of the five phases of IDEAL is described below.

Initiate phase

In this phase, a foundation is laid for a series of successful improvement efforts. The phase starts when a stimulus for improvement is identified and understood by the relevant stakeholders. At the end of this phase, a strategic improvement plan (SIP) is developed that defines the time horizon and overall goals of the improvement activity. A typical time horizon is equivalent to the length of at least two improvement cycles. The primary tasks associated with the Initiate phase are summarized in the Factbox.

Research centers at ABB have developed several tools and methodologies that are used during the Initiate phase of IDEAL. A business decision-making model is used to identify the business benefits of an improvement project. An assessment is made of a BU's readiness for change. The assessment identifies areas of possible resistance to change, and provides a plan to prepare the way so that the organization can embrace the proposed improvement. An SIP is created, which is designed to ensure that each improvement activity within the BU is supported with appropriate resources.

> ABB employs the IDEAL℠ model to collaboratively establish, execute and accelerate improvement programs.

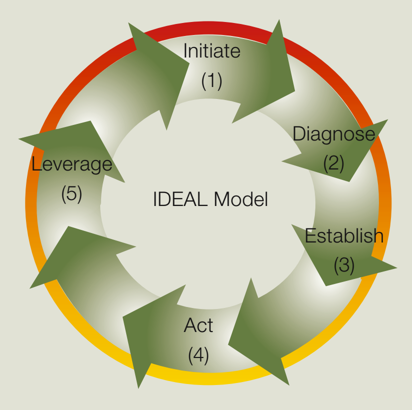
Diagnose phase

This phase in the improvement program establishes an understanding of the current technologies, processes and organizational interactions, which are documented to create a baseline for the improvement activity. This information supports the improvement planning and prioritization process, and acts as an indicator to help track and verify the impact of the program's activities. The main tasks of this phase are to:

1) Determine how many and what types of diagnostics are required to define the organization's baseline with respect to the planned improvement activity.
2) Plan for the activities, resources, and skills required for the diagnostic activities.
3) Conduct the diagnostic activity to identify the strengths and weaknesses of the BU with respect to the improvement goals.
4) Communicate and document the findings to the organization.

Several internal diagnostic tools have been developed by the ABB research centers for evaluating product architectures[1], technologies, and processes, all based on sound engineering

1 IDEAL improvement cycle



Factbox Tasks associated with the Initiate phase

1) Define the approach to run the improvement program.
2) Identify the business needs and drivers for improvement from the management view point.
3) Assess the organizational readiness for the improvement program and use this information to define management strategies.
4) Write an SIP, and obtain both approval and commitment of resources from senior management.
5) Create awareness, set expectations, and build support for the forthcoming improvement program within the BU.
6) Establish the infrastructure to provide visibility and support for the improvement program.
7) Define measurable goals for the improvement program.
8) Launch the improvement program.

Footnote

[1] Product architecture encompasses the structure that integrates the components and the subsystems of a product into a coherent mechanism to perform an intended function and also considers its methods of use, methods of maintenance, and its production.

Sustainable results

principles and proven methodologies developed in industry and academia. To evaluate product and system architectures, ABB has tailored a software architecture approach using the attribute-driven design (ADD) and Architecture Tradeoff Analysis Method® (ATAM®) developed at the SEI [2,3,4,6]. To evaluate technologies, the company has developed an Attribute Hierarchy-based Evaluation of Architectural Designs (AHEAD) methodology, based upon the Analytic Hierarchy Process (AHP) approach [7]. For diagnosing product development processes, ABB has developed an internal appraisal method, based on the Standard CMMI® Appraisal Method for Process Improvement® (SCAMPI®) [5].

Establish phase

This phase establishes the foundation for the actions of a specific improvement cycle. The course of action taken is determined by the results of the diagnostic activity. To implement this decision, a plan to make the appropriate changes (introduce a new technology, develop a new product, make improvements in processes or change the architecture of a product) is developed, which draws on the vision established during the Initiate phase. The primary tasks of the Establish phase are to:

1) Review the BU's vision, business plan, key business issues, and motivations identified in the Initiate phase, and realign the improvement program objectives if necessary.
2) Update the SIP as necessary.
3) Based on the final findings identified during the Diagnose phase and the BU's business objectives, choose and prioritize activities, and develop the tactical improvement plan (TIP). This plan guides the improvement activity during the cycle.
4) Build consensus, review, obtain senior management approval for the TIP, and commit the resources to action.
5) Establish the technical working groups (TWGs) who will be responsible for implementing the TIP.

Act phase

In this phase, the TIP is put into action. The improvements are developed, piloted, and deployed across the BU by the TWGs. The primary tasks in this phase are to:

1) Execute the TIP as a project.
2) Develop and pilot potential solutions as identified in the TIP.
3) Collect and analyze pilot results and derive lessons learned in the improvement project.
4) Develop roll-out strategies based on pilot results and lessons learned.
5) Roll out the selected solutions, providing long-term support to ensure smooth transition.

During the Act phase, good project management practices are used to ensure that the improvement projects remain on schedule, on budget, and deliver the expected results.

Leverage phase

The objectives of this phase are to analyze how the improvement cycle was carried out, to assemble the lessons learned, and to incorporate these lessons learned into the SIP that will be used in the next improvement cycle. The Leverage phase feeds into the Initiate phase for the second improvement cycle. The primary activities of the Leverage phase are to:

1) Gather lessons learned during the improvement cycle.
2) Analyze lessons learned and decide how to utilize them in future cycles.

Once the Leverage phase has been completed, a new improvement cycle begins, starting again with another Initiate phase that is consistent with the SIP.

The IDEAL model ensures that the introductions of new technologies, products, or improvements in ABB are based on strong business drivers.

To ensure the improvement strategy is implemented effectively, an agent for change is assigned authority and responsibility for organizing, planning, staffing, monitoring and directing the improvement program to ensure that the activities of the entire IDEAL cycle are performed effectively.

Use of IDEAL at ABB

The IDEAL model has been used in many of ABB's BUs. The following examples illustrate two particular cases. The first and more detailed example describes a software process improvement project at a product development BU. The second relates to a project focused on re-architecting[2] a software product in another BU.

Footnotes

[2] Rework on software is the potentially avoidable work that is required to correct problems or tune an application.

[3] Goal-question-metric (GQM) is a goal-driven method that uses metrics to improve the software development process (and its resulting software products) while maintaining alignment with business organization and technical goals.

Software process improvement

At the inception of this project, senior managers identified several organizational business goals. One of the most significant was to reduce the cost of rework[2] by a defined percentage after software integration testing. ABB Corporate Research partnered with the BU to help to achieve this goal, applying the IDEAL model as a fundamental part of the improvement activity.

Initiate

During the initiation phase, the BU senior management defined specific reductions in software rework targets as the business goal. They identified a minimum time horizon of two years in which continuous software process improvement activity would be addressed, not only to achieve the immediate business goal, but also to address future goals related to software process improvement. A decision was also made to seek support from Corporate Research for this activity. To this end, a team responsible for the process improvement project was created, including an agent for change from the BU, together with two software engineering experts from Corporate Research.

To guide the software development improvement process, CMMI® v1.2, developed by the SEI, was used. The metric employed to measure the success of the improvement program was to monitor the time required to rework software, ie, the time taken to remove software product defects identified after integration testing.

An organizational change-readiness assessment was conducted that considered a variety of factors within four categories: 1) organizational acceptance to change; 2) commitment to the sponsor; 3) willingness of the change agent to drive change forward; and 4) the organizational expertise available for the implementation of change. The results of this assessment are summarized in 2.

The IDEAL model helps foster a continuous improvement culture in the organization.

A thorough analysis of the results showed that the change agent required technical training in CMMI and change management, and needed to increase his time commitment to the improvement project. The sponsor needed to "walk the talk," demonstrating his commitment to the improvement project to the rest of the organization. Finally, the organization needed technical training to better understand the good development practices that underpin the CMMI.

Diagnose

To define a process improvement baseline, a diagnosis of the BU's development process was conducted using the CMMI model and ABB's internal CMMI appraisal method. This appraisal resulted in the identification of strengths and potential areas for improvement in the BU's processes, which would reduce rework after integration testing.

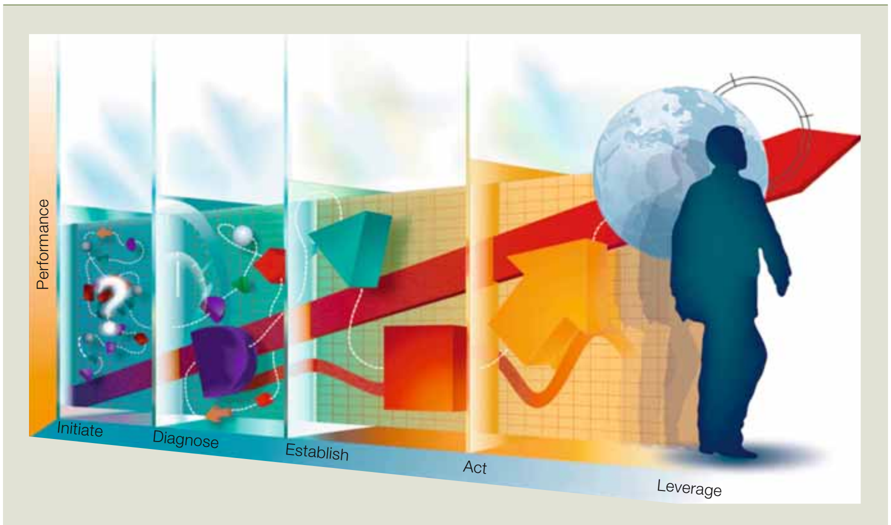
ABB's drive towards continuous improvement highlights its commitment to enhance products and services.

Establish

Using the goal question metric (GQM)[3] analysis, priority areas that would support the achievement of the business goal were identified. One area selected for improvement was Requirements Management (REQM). Although the BU had a strong Requirements Engineering (RE) process[4], it was performed manually. Natural changes in requirements during the development life cycle were not captured fast enough, resulting in large amounts of software rework after system testing. With this information, a TIP was created to provide automation support for the RE process and a TWG was launched.

Act

During this phase, the TIP generated to improve and automate the RE process at the BU was successfully carried out. The project focused on using



2 Organizational change chart for the software process improvement project

Footnote

[4] The Requirements Engineering process described in this article is the combination of both Requirements Development and Requirements Management processes. Requirements Development refers to eliciting, producing, and analyzing all the requirements associated with a development project, including both technical and non-technical requirements. Requirements Management refers to the management of all requirements and change requests received or generated by the development project.

the basic elements of the existing process and enhancing it so that it could be automated. Once the new RE process was completed, it was piloted and then rolled out to the organization.

Leverage

At the end of the first cycle of the continuous software development process improvement activity, the quality group in the development organization gathered measurements and reported that, due to the improvement to the RE process, a 30 percent reduction in the software rework effort was achieved. During the leverage phase, the improvement team identified aspects of the improvement project that worked well and aspects that did not work as expected. An area that was deemed very important was enhancing the communication between the change agent and the sponsor. Additionally, senior management in the BU decided to continue the project as planned for another one-year cycle to address additional areas of potential improvement.

Re-architecting a software product

In a second example, senior management at an ABB product development BU identified an important business goal to increase their market penetration by a defined percentage. Several options were considered by the BU to meet this business goal. The BU selected the option of re-architecting their main product, and began by investigating the use of a different software technology for its development.

A willingness to adapt rapidly to changing markets and to adopt new technologies is essential in a highly competitive business environment.

Initiate

Based on the management commitment to redesign the product, a high-level agreement and plan were jointly developed by the BU and research centers, committing resources to complete the project within a certain time horizon. A set of metrics was identified that emphasized the importance of maintenance costs and the value of market penetration. Furthermore, an assessment of the readiness of the BU to redesign their main product using a new technology was conducted. Re-architecting a software product using a different software technology highlighted the possibility that software developers might need further training.

Diagnose

After defining the required software quality attributes that were most important for the product, a set of architectural scenarios was generated and used to evaluate the current product design, using ABB's internal ADD-based method for software architecture evaluation.

Establish

A detailed plan was created to evaluate and select new software designs.

Act

The actual evaluation of software design options was performed using the AHP-based AHEAD [7] method for technology evaluation, and a prototype of the product incorporating the selected design was developed.

Leverage

Lessons learned were collected and documented.

The primary activities carried out while using the IDEAL model in both software process improvement and product re-architecting are summarized in 3.

3 A summary of the primary activities carried out while using the IDEAL model in both software process improvement and product re-architecting

IDEAL[SM] 1.0 phase	Software process improvement	New product design
Initiate	1) Reduced cost of integration testing by a defined percentage 2) Ran a continuous software process improvement project for at least two years 3) Created a responsible team for software process improvement 4) Used CMMI as improvement model 5) Selected rework time as metric to be monitored 6) Made a readiness assessment that indicated the need to increase sponsor and change agent commitment as well as organizational training 7) Created SIP for process improvement	1) Increased market penetration by a defined percentage 2) Redesigned current main product and investigated the use of new technologies 3) Used ADD method to redesign product 4) Selected metrics of increased percent of market penetration and reduced maintenance cost 5) Made a readiness assessment that indicated the need to provide organizational training in new technology 6) Created SIP for redesigning product
Diagnose	1) Internal CMMI appraisal was conducted by Corporate Research to create a baseline of process areas at the BU	1) Developed design scenarios based on product quality attributes 2) Used ATAM (from the SEI) to diagnose current product design
Establish	1) Used GQM approach to prioritize improvement activities 2) Developed prioritized TIP for process improvement 3) TWG created and assigned	1) Created plan to redesign product and evaluated suitable software technologies for implementation 2) Developed TIP for redesign project
Act	1) RE process enhanced and automated 2) New process tested in pilot development project	1) Built new product designs and prototypes using candidate technologies 2) Used AHP to evaluate prototypes and design options, and selected a technology
Leverage	1) Measured percentage reduction in integration testing costs (result: even higher than expected) 2) Documented lessons learned	1) Documented lessons learned

The leveraging of lessons learned helps to ensure that the improvement activities have a positive impact on the products and services ABB offers to its customers.

Benefits of using the IDEAL model

Several benefits have been observed in using the IDEAL 1.0 model. These benefits are summarized below.

First, the IDEAL model ensures that the introductions of new technologies, products, or improvements in ABB are based on strong business drivers, which in turn reflect market demands, responding to customers' needs, and the desire to continually improve our competitive position. Second, the IDEAL model systematically establishes a solid framework for change at the affected BUs, building strong commitment to the desired improvement or change. This, in turn, translates into commitment to our ABB customers to support the new technology or product and to ensure that proper migration paths are developed. Third, the IDEAL model is a great tool for planning the necessary resources and effort required to implement the improvement or change, which in turn increases customer confidence that ABB is a committed partner providing the product or service improvements they need. Fourth, the IDEAL model fosters a continuous improvement culture in the organization. Continuous improvement means that we are committed to constantly search for opportunities to enhance the products and services we provide to our customers and to listen and act on our customers' needs. Finally, the Leverage phase of the IDEAL model provides a useful mechanism to collect lessons learned on each improvement activity, which can be stored, indexed, and accessed when a new improvement cycle begins. This leveraging of lessons learned helps to ensure that the improvement activities have a positive impact on the products and services ABB offers to its customers.

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References

[1] Software Engineering Institute (SEI). IDEAL^{SM} Model: Initiating, diagnosing, establishing, acting and learning. Retrieved February 2009 from http://www.sei.cmu.edu/ideal/

[2] Software Engineering Institute (SEI), Attribute-driven design method (ADD). Retrieved February 2009 from http://www.sei.cmu.edu/productlines/add_method.html

[3] Software Engineering Institute (SEI), The architecture trade off analysis method (ATAM). Retrieved February 2009 from http://www.sei.cmu.edu/architecture/ata_method.html

[4] **Bass, L., Clements, P., Kazman, R.** (2003). *Software architecture in practice*. Addison-Wesley.

[5] **Bush, M., Dunaway, D.** (2005). *CMMI Assessments: Motivating positive change*. Addison-Wesley.

[6] **Clements, P., Kazman, R., Klein, M.** (2002). *Evaluating software architectures*. Addison-Wesley.

[7] **Smiley, K., He, Q., Kielczewski, E., Dagnino, A.** (2009). Architectural requirements prioritization and analysis applied to software technology evaluation. *Proceedings of the 24th Annual ACM Symposium on Applied Computing* (SAC'09).

Further reading

Börjesson, A., Mathiassen, L. (2002). Making SPI happen: The IDEAL distribution of effort. *Proceedings of the 36th Hawaii international conference on system sciences* (HICSS'03).

Kinnula, A. (2001, September). Software process engineering systems: Models and industry cases. Report, Department of Information Processing Science, University of Oulu.

Mathiassen, L., Ngwenyama, O. K., Aaen, I. (2005). Managing change in software process improvement. *IEEE Software*, November/December, 84–91.

McFeeley, R. (1996). IDEAL^{SM} – A user's guide to software process improvement. CMU/SEI-96-HB-001, Software Engineering Institute (SEI).

Reliability analysis

Data and modeling software is helping an NGL plant determine maintenance approaches and improve equipment reliability

Fernando Vicente, Hector Kessel, Richard M.Rockwood

Over the past several years, reliability – ie, the probability that a product, equipment or process will perform its intended function, without failure, under specific conditions for a specific period of time – has become an increasingly important topic when it comes to continuous improvement. Higher plant reliability reduces process- and equipment-failure costs, and contributes to increased production – and thus a greater gross margin. In addition, it increases workplace safety and reduces potentially serious environmental risks.

Today, in the intensively competitive oil & gas industry, gas plants must operate at a high level of reliability without wasting money or incurring extra costs. ABB is helping such companies to achieve this goal by using objective, quantifiable measures to address equipment failures at earlier stages of failure development. This article presents three specific examples of reliability analysis performed at MEGA's Loma La Lata site in Argentina. And the results – savings!

Enlightened organizations strive for zero defects and zero accidents. Many of those same organizations also apply the "zero tolerance" rule to equipment failures and have a goal of zero failures. However, equipment that is left unattended will eventually fail. To address this, leading organizations are implementing two important equipment management strategies: condition-based maintenance, and reliability practices. The key factor is to obtain control of failures by anticipating them early on and intervening with planned and scheduled approaches.

Reliability practices are making great contributions in this two-pronged strategy, as is shown in the following three case studies. The first examines the reliability analysis of a natural gas liquids (NGL) pump's mechanical seal; the second looks at the validation of a modification in a screw compressor; and the third addresses the reliability analysis of a temperature transmitter (TT).

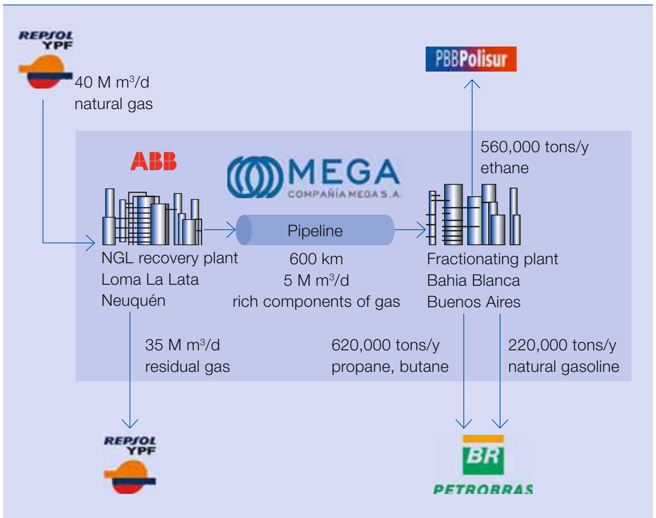
MEGA – ABB Full Service® partnership

As part of its ABB Full Service® contract with MEGA (a gas plant located at the Loma La Lata site in Neuquen, Argentina), ABB is responsible for mechanical, electrical, instrumentation, and static management, as well as static inspection, planning, scheduling, and complete material management of spare parts.

> To truly compete in a global environment, an organization needs not only high equipment availability, but also high equipment reliability – selecting the best approach is key.

The MEGA facility is responsible for the recovery and separation of NGL. This process involves separating the methane from other NGL components and then injecting the methane back into a pipeline that supplies the domestic market. The other components are piped to another facility located in Bahia Blanca for further processing. This facility is a fractionating plant that separates the NGL into ethane, propane, butane, and gasoline, which are then sold to their customers – namely, the Argentine government and the Bahia Blanca facility 1.

1 MEGA gas plant operations at the Loma La Lata site in Argentina



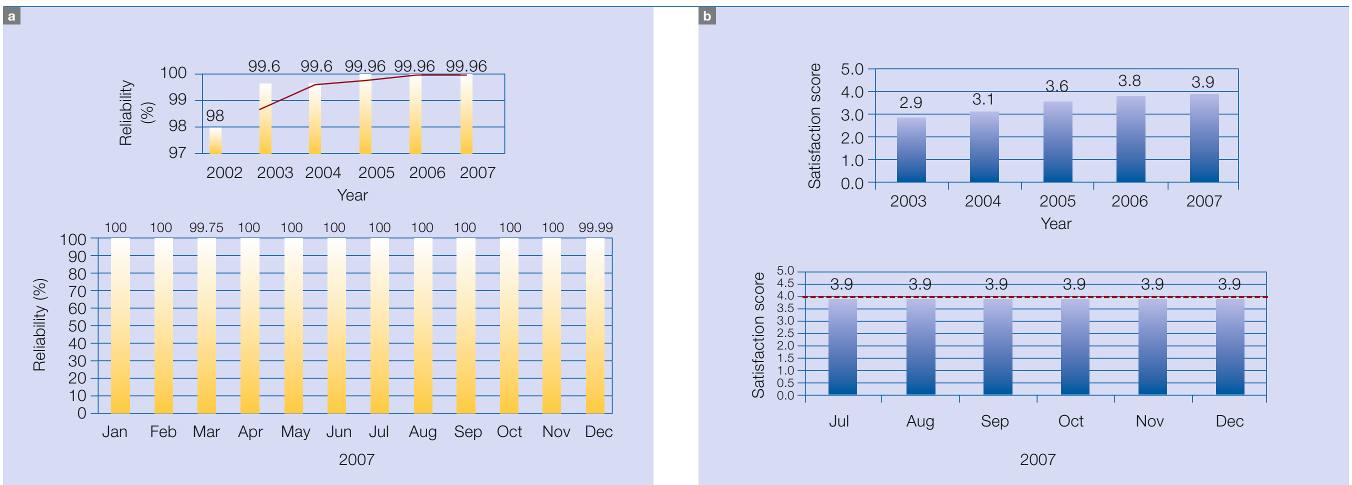
Meeting customer expectations

Equipment availability is approaching world-class levels 2. However, this indicator reflects the availability of process-critical equipment, much of it with offline spares or online backup equipment. As a Full Service provider, ABB is expected to deliver the latest in service technology and leading-edge management practices. Thus ABB was asked to start focusing on other process-critical equipment and increase availability to levels that could result in running the plant based on market demand.

From assistance to action

The annual Full Service site assessment was completed at MEGA in early 2008. Site assessments identify initiatives that are performing well and also identify those that can be improved. Each assessment comes with recommendations to assist the ABB site team in closing those performance gaps that have been identified.

2 Equipment reliability trends a, where the goal was 99.6 percent, and customer satisfaction trends b, where the goal was a score of 4.0 out of a possible 5.0



Sustainable results

While the site assessment process at MEGA was very effective, it became evident that more could be done to help the sites improve in both the quality and quantity of the "gap-closing" initiatives. This meant improving the execution of initiatives with the goal of improving client, ABB, and people value, mirroring the ABB Full Service results triangle 3. This approach has been coined "post-assessment assistance" Factbox 1.

The key factor is to obtain control of failures by anticipating them early on and intervening with planned and scheduled approaches.

The post-assessment assistance develops a specific way forward, a road map unique to each site. It contains the objectives, goals and site-specific initiatives designed to close gaps in site performance and client expectations 4.

Reliability in practice

For most individuals, reliability numbers, by themselves, lack meaning for making improvements, regardless whether the numbers are percentages, mean time between failures (MTBF) or fewer emergency work orders written. For business, the financial issue of reliability means controlling the cost of unreliability from equipment and process failures, which waste money and impact production capacity.

From an engineering perspective, reliability is commonly quantified by determining the probability of a failure occurring. Attempts to measure probability involve the use of probabilistic and statistical methods and tools. Typical examples of reliability analysis used in gas plants include the use of different reliability tools, such as Weibull analysis, Pareto analysis and Monte Carlo simulation Factbox 2.

A key factor for reliability analysis is the quality of plant data – specifically, how the data is obtained, managed, and who is responsible for analyzing it. Most plants in the oil & gas industry have accumulated data for many years, but it is rare to find someone who is responsible for analyzing the data and for obtaining information that can be used in problem-solving exercises.

Plant data is an excellent means of showing what works, and also for showing improvement opportunities. A good approach for beginning the analysis is to locate the problems by examining the frequency of occurrence. The first tool to consult for a brief overview is the "top 10" Pareto chart. Pareto analysis is used to rank the opportunities and to focus on those with the highest values. The proverbial 80/20 rule applies: 80 percent of the problems or losses are driven by 20 percent of the equipment or processes 5.

Reliability analysis: mechanical seal in an NGL pump

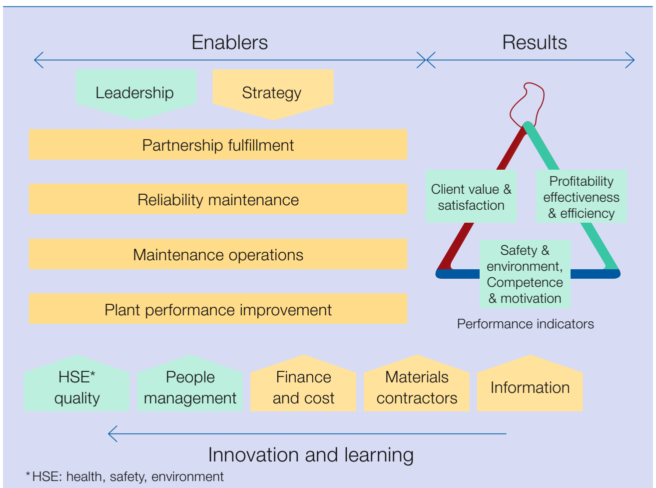
Based on the Pareto analysis, the ABB engineering team chose to analyze the reliability of the NGL pump 510-P-01C. The team believed that the pump system had low reliability because the process condition had varied from the original design condition.

Typical examples of reliability analysis used in gas plants include the use of different reliability tools, such as Weibull analysis, Pareto analysis and Monte Carlo simulation.

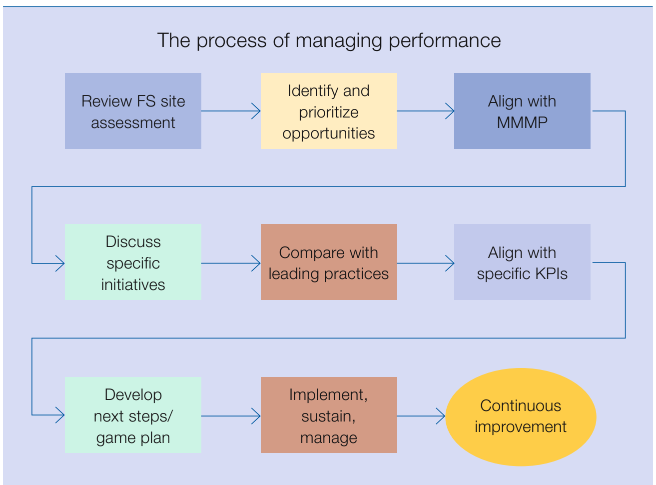
Next, a search of the Computerized Maintenance Management System (CMMS) database on NGL pump 510-P-01C revealed that the most frequent failure mode was associated with mechanical seal failure.

It is often said in reliability professional circles that maintenance is managed at the failure-mode level. Failure mode is defined as any event that is likely to cause an asset (or system or process) to fail. Thus, a failure mode is an event that causes a functional failure in an asset. Common failure

3 The site assessment process is an effective tool used to ascertain not only current performance but is also highly effective in developing forward thinking strategies

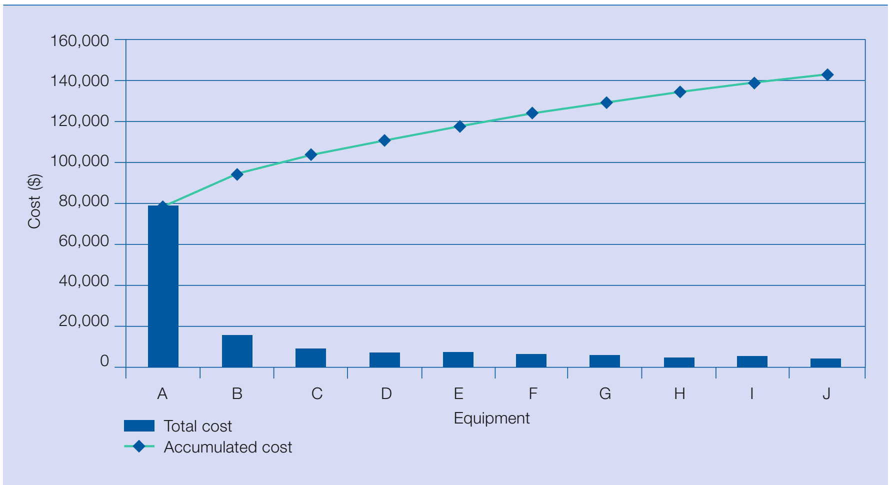


4 Post-assessment assistance



Sustainable results

5 Pareto chart showing the top 10 improvement opportunities at MEGA . In June through August, equipment A accounted for 80 percent of the cost.



6 NGL pump data collected from the CMMS database

Age (hours)	Failure (F) or suspension (S)
9,236	F
2,924	S
2,202	F
12,433	F
11,123	F
2,880	F

Preventive replacement cost (before failure) = $4,258
Mean time to repair (MTTR) = 5 hours
Failure cost (lost production + replacement cost) = $413,403

modes are: bearing seized, impeller jammed, motor burned out, and blocked suction line.

The NGL pump is a critical piece of equipment for the production process since it delivers the final processed product to the Bahia Blanca plant, where it is fractionated into other products (ethane, propane and butane). Based on the CMMS data collected for this pump, reliability application software was selected because of its capability to perform Weibull analysis. The equation used to calculate reliability is:

$$R_t = e^{-\left(\frac{t}{\eta}\right)^{\beta}}, \ t > 0$$

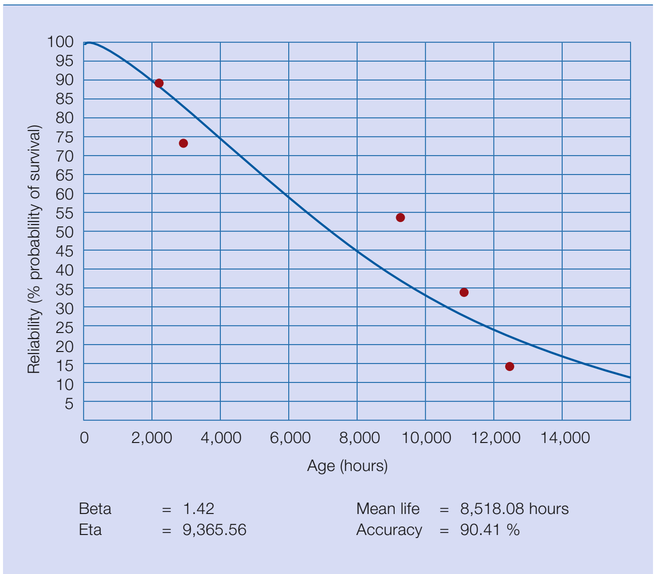
where:
R(t) = reliability value (0-1)
t = age of failure (hours, cycles)
η = scale parameter (hours, cycles)
β = shape parameter (β<1; β=1; β>1)

The data collected from the CMMS database is shown in 6. Weibull analysis revealed the failure pattern results depicted in 7.

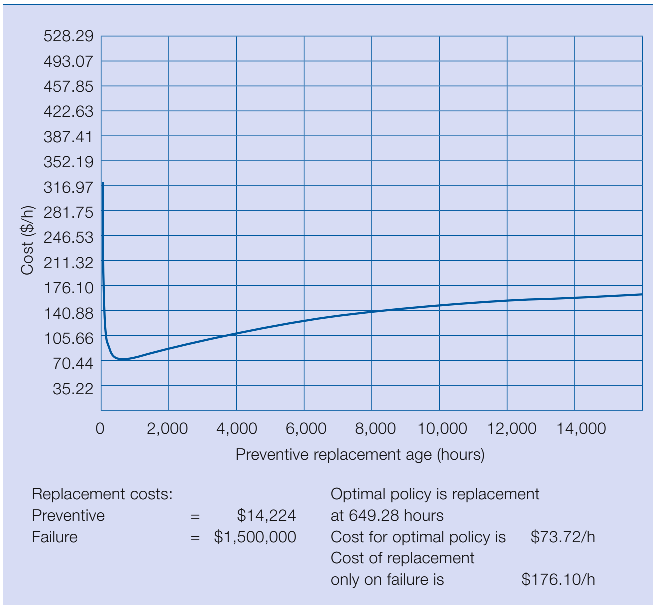
One of the advantages of using Weibull analysis is the fact that it provides a flexible modeling profile covering early-life, random, and wear-out failure patterns. For the mechanical seal, the MTBF is 8,518 hours, which indicates that 50 percent of the mechanical pump seals fail before they reach 8,518 hours of operation, and 50 percent fail after 8,518 hours of operation. This analysis motivated the customer to upgrade the pump system by improving the mechanical seal.

Next, the ABB team performed a cost analysis to ascertain the optimal time to make a spare-part (mechanical-seal) replacement. 8 shows that the optimal time to replace the mechanical seal is at about 650 hours of operation, which would yield a per-hour operations savings of $103. However, this replacement frequency was deemed impractical, so the ABB team

7 Reliability function of the NGL pump as demonstrated with Weibull analysis (two parameter, linear regression)



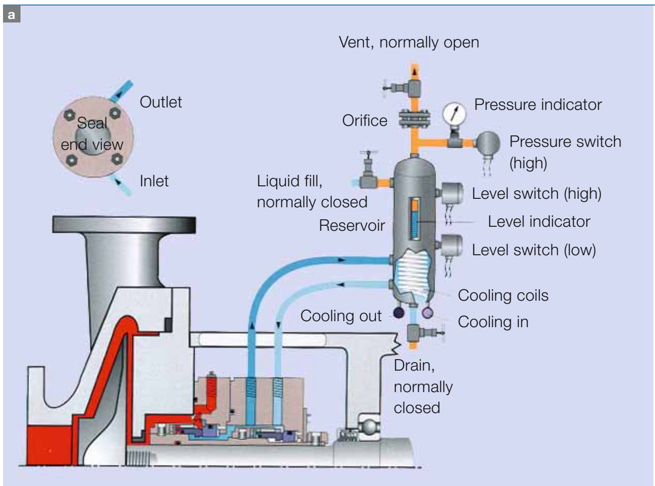
8 Replacement policy analysis



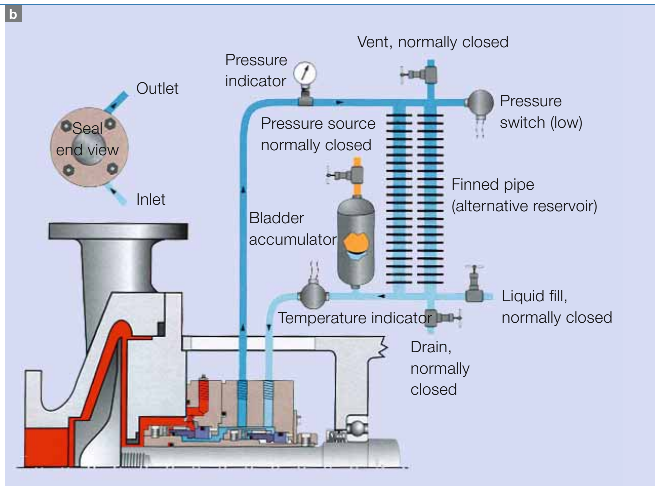
Sustainable results

9 Actual plan the American Petroleum Institute (API) installed on pumps a, and the new plan proposed by the API b. Even process conditions can be changed: The pressure on the seal will be the design condition.

a



b



analyzed potential replacements at several different hours of operation.

The second analysis at 4,000 hours of operation resulted in a savings of $66 per hour of operation. The team then performed a third analysis at 6,000 hours of operation, which yielded a cost savings of $46 per hour. Finally, a fourth analysis at 8,000 hours of operation yielded a cost savings of $36 per hour.

As a result of the Weibull analysis, the ABB team could make several recommendations. After careful consideration, MEGA and ABB agreed that a redesign or modification was preferred over implementing a maintenance strategy based on periodic replacement. The modification agreed upon was to install a pressurized system that would activate the mechanical seal 9.

The proverbial 80/20 rule applies: 80 percent of the problems or losses are driven by 20 percent of the equipment or processes.

The cost of the modification (two seals per pump) is approximately $90,000. The reliability of the modification will be monitored by regular data analysis using the Weibull method, making it possible to determine the improvement in reliability through extending the MTBF beyond the originally established baseline.

Weibull analysis of a screw compressor

The air screw compressor is classified as process-critical equipment. The function of the compressor is to supply oil with air for the plant instrumentation. What makes this a critical step in the production process is that, if air was not supplied, plant instrumentation would malfunction and lead to erroneous readings, resulting in production control variation.

Some unexpected failures occurred in the resistance temperature detector (RTD) sensor. The RTD is a device that measures the air temperature discharge; if it fails, the screw compressor stops. After performing root cause failure analysis (RCFA), the ABB team concluded that the main failure mode was caused by high vibration when the compressor was in operation.

The team then designed a device to absorb vibration, which thus should reduce failures 10 11. But the question remained: Did the modification reduce the vibration failure mode and im-

Factbox 1 Post-assessment assistance

After an ABB Full Service site successfully completes an assessment, the post-assessment assistance offering helps address the findings and recommendations designed to improve site performance. Each site receives a customized "way forward" strategy tailored to reflect its unique challenges and improvement opportunities. Then, the improvement opportunities are addressed in a logical, step-by-step plan. This process was used at MEGA and addressed one of the findings from the assessment, which was to improve the site's approach to reliability. ABB worked with the MEGA site to understand how implementing reliability would benefit the site. The ABB site-reliability team then identified specific opportunities in which to apply a reliability-based improvement initiative.

Factbox 2 Reliability application software selection

Data analysis can be improved through the use of reliability software capable of statistical analysis. Reliability software was used in decision making for the three case studies in this article. Whatever reliability application software is selected should have the functionality to perform Weibull analysis. The Weibull method identifies or models the category of failure – early life, random, and wear out – based on the operating time (ie, equipment age) at which a component fails. Because Weibull analysis can fit most data better than other models and is effective in providing accurate failure analysis with relatively small data samples, it is the most widely used model for determining component reliability analysis and has emerged as the preferred method to model and analyze component failure patterns.

10 An anti-vibration device a b was placed on the RTD sensor c to reduce RTD failures.

11 Failure in the RTD wire due to high vibration acting on the system

prove reliability? Weibull analysis was used to assess the level of reliability improvement.

With a pre-modification MTBF of 3,042 operating hours and a post-modification MTBF of 5,000 operating hours, the actual improvement is approximately 2,000 operating hours – a 19 percent MTBF improvement 12 13. The ABB team will monitor the MTBF for improvement and address the next predominant failure mode.

Reliability analysis of temperature transmitter

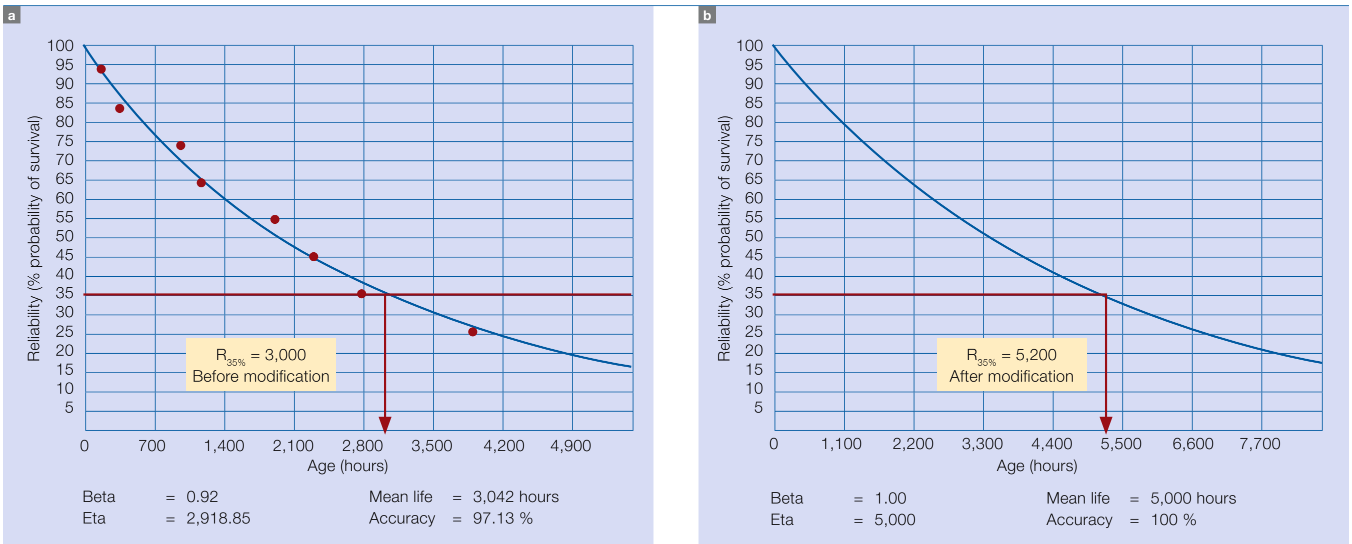
Temperature transmitters (TTs) control the temperature in process-sensitive automation controls. This equipment was selected as a result of numerous failures over the past year. The failures appeared to be random in nature (ie, no predominant failure pattern), making reliability improvements challenging.

Weibull analysis provides a flexible modeling profile covering early-life, random, and wear-out failure patterns.

The ABB team collected all failure data from the CMMS equipment history in order to perform a reliability analysis. Failure data pertaining to the TT was collected from the CMMS system for the period from 2001 to 2008. Next, the team used the reliability application tool to model a reliability curve to identify any failure patterns 14.

Simply plotting the data yielded some surprising results. The MTBF was calculated at 61 months or approximately 5 years. Looking at other similar equipment in the industry, a typical MTBF is between 25 and 150 years. The ABB team thus pursued further data analysis and testing of similar equipment in a laboratory setting. It was determined that the problem was actually inside the instrument and the root cause was the design from the original equipment manufacturer (OEM). This analysis lead to a discussion between MEGA and the OEM, and resulted in MEGA receiving a credit for previous TT equipment failures and also provided data to the OEM for creating a new improved version.

12 Reliability function of RTD before modification (using two-parameter, maximum-accuracy Weibull analysis) a, and after modification (using two-parameter, linear-regression Weibull analysis) b.

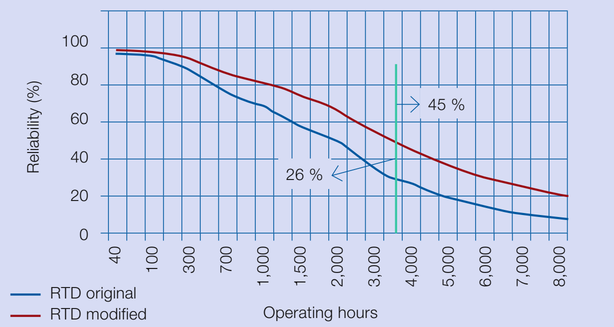


Sustainable results

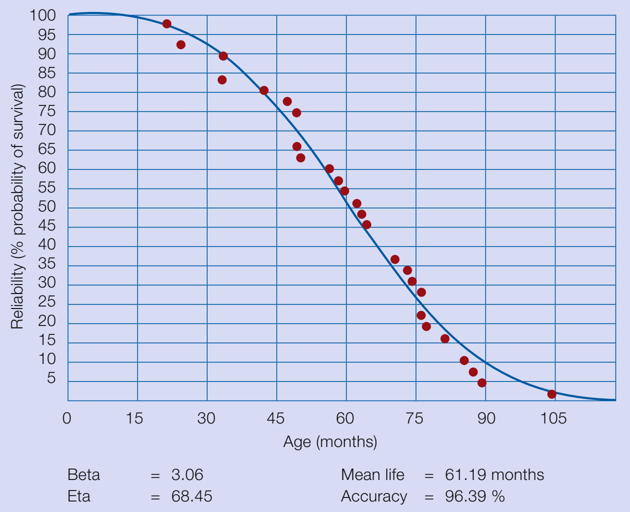
High reliability is a high priority

The strong competitive environment between companies to secure business and the current world financial crisis are forcing organizations to explore ways to reduce operating costs. A popular approach is to reduce expenditures on equipment maintenance. However, this is very short sighted, as deferred investments often resurface and can cost two to five times more than if they had been addressed in the early stages of failure development.

13 Reliability curves comparison. After modifying the RTD sensor, the MTBF improved by 19 percent.



14 TT reliability curve



> Data analysis resulted in MEGA receiving a credit for previous TT equipment failures and also provided data to the OEM for creating a new improved version.

Timely maintenance of equipment with the subsequent improvement in reliability will reduce the overall cost of not only equipment unreliability but also process-related unreliability. Together, this approach will improve business performance and generate more profits, and can result in incremental business given the increase of production capacity resulting from higher production uptime or availability. Additionally, the higher production output will offset the cost of additional investment in equipment, thus lowering maintenance costs.

Various strategies and tools are available that can be used to assist in making the best maintenance and replacement decisions. The intent of these decisions is to determine the type of maintenance tactic required for preserving system function. In particular, utilizing reliability-based application software with Weibull functionality can yield improved objective decision-making capabilities.

> Deferred investments often resurface and can cost two to five times more than if they had been addressed in the early stages of failure development.

To truly compete in a global environment, an organization needs not only high equipment availability, but also high equipment reliability. Knowing what equipment management tactic to deploy can be challenging given choices between preventive maintenance replacement intervals, inspection frequencies, condition-based maintenance actions, capital equipment replacement and maintenance resource requirements. Selecting the optimal maintenance approach can increase the likelihood of realizing lower operating costs and higher levels of reliability and availability, resulting in more reliable production. The optimal approach can support initiatives designed to deliver positive results in client, people and ABB value.

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Further reading

Desaegher, J. (2008). Outsourced maintenance: The ABB Full Service® solution. *ABB Review Special Report: Process Automation Services and Capabilities*, 79–83.
Kleine, B. What is reliability? Changing the reliability paradigm. *ABB Review* 1/2009, 34–37.

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The energy link

Electricity is a driving force of the economy and indeed of human society as we know it. But it is not just the basic availability of this energy that is taken so for granted: Both industrial and domestic users rightly expect its supply to fulfill the highest standards of reliability and predictability.

The vital infrastructure that makes this possible is continuously developing and must fulfill rapidly changing demands. Increased trading of power means that electricity is being transported over longer distances, placing new demands on infrastructure. The rapid development of emerging economies is leading to massive investment in long-distance transmission to keep the lights on in the major cities. At the same time the search for alternative sources of energy is leading to a boom in renewables. The variable availability of the latter creates new challenges, for example in scheduling or because generation is often concentrated in sparsely inhabited areas where the existing infrastructure was not designed to cope with such an influx of power. All these factors are calling for new approaches in the planning and operation of electricity supplies. One possible solution lies in the transition to so-called smart grids, in which state-of-the-art control and monitoring methods permit the transmission infrastructure to be used with a flexibility that was previously not possible – and this without compromising its reliability and robustness. The upcoming edition of *ABB Review* will investigate some of the technologies required for this to happen.

We trust you will have an energizing read.