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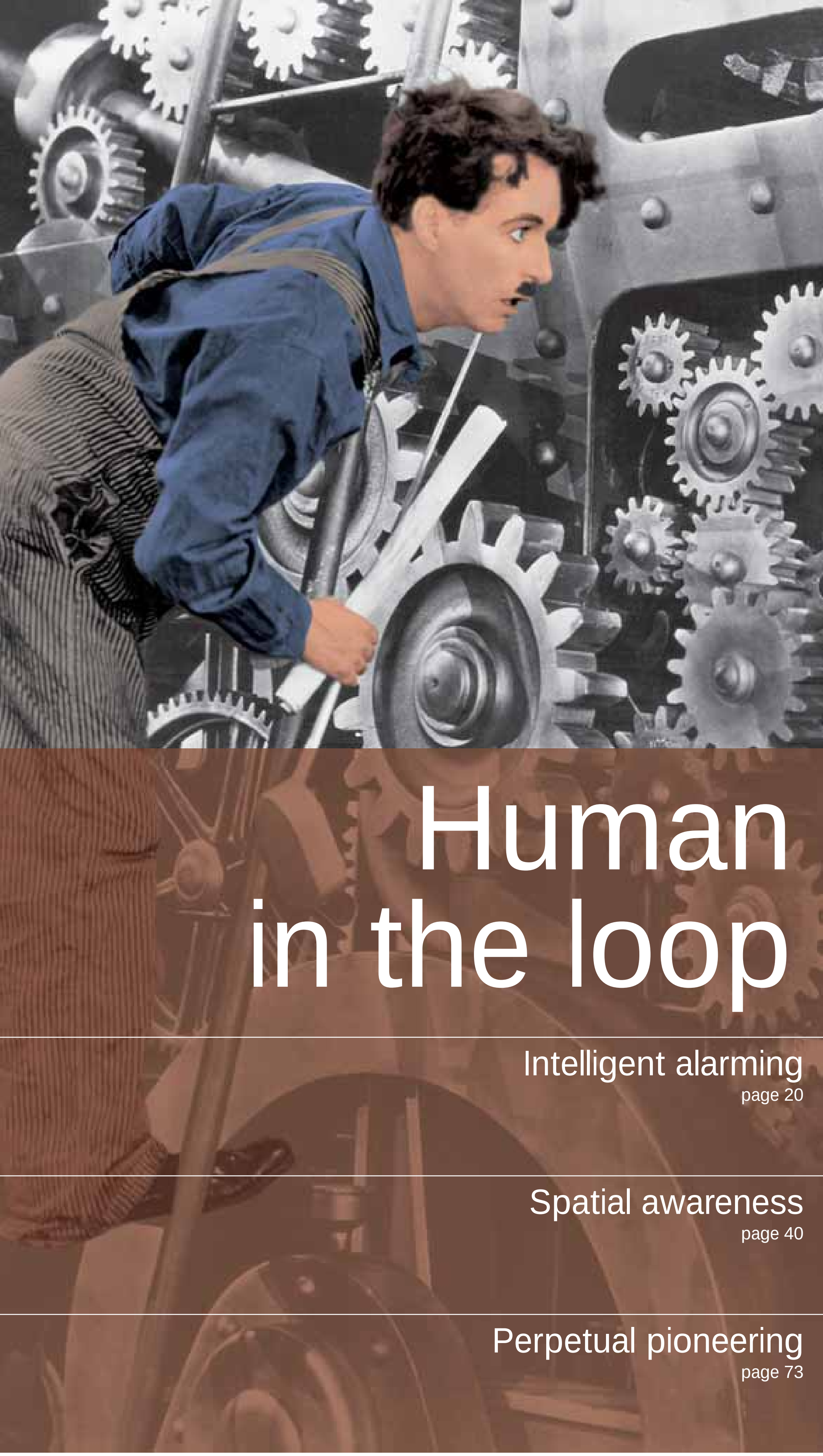

# Human in the loop



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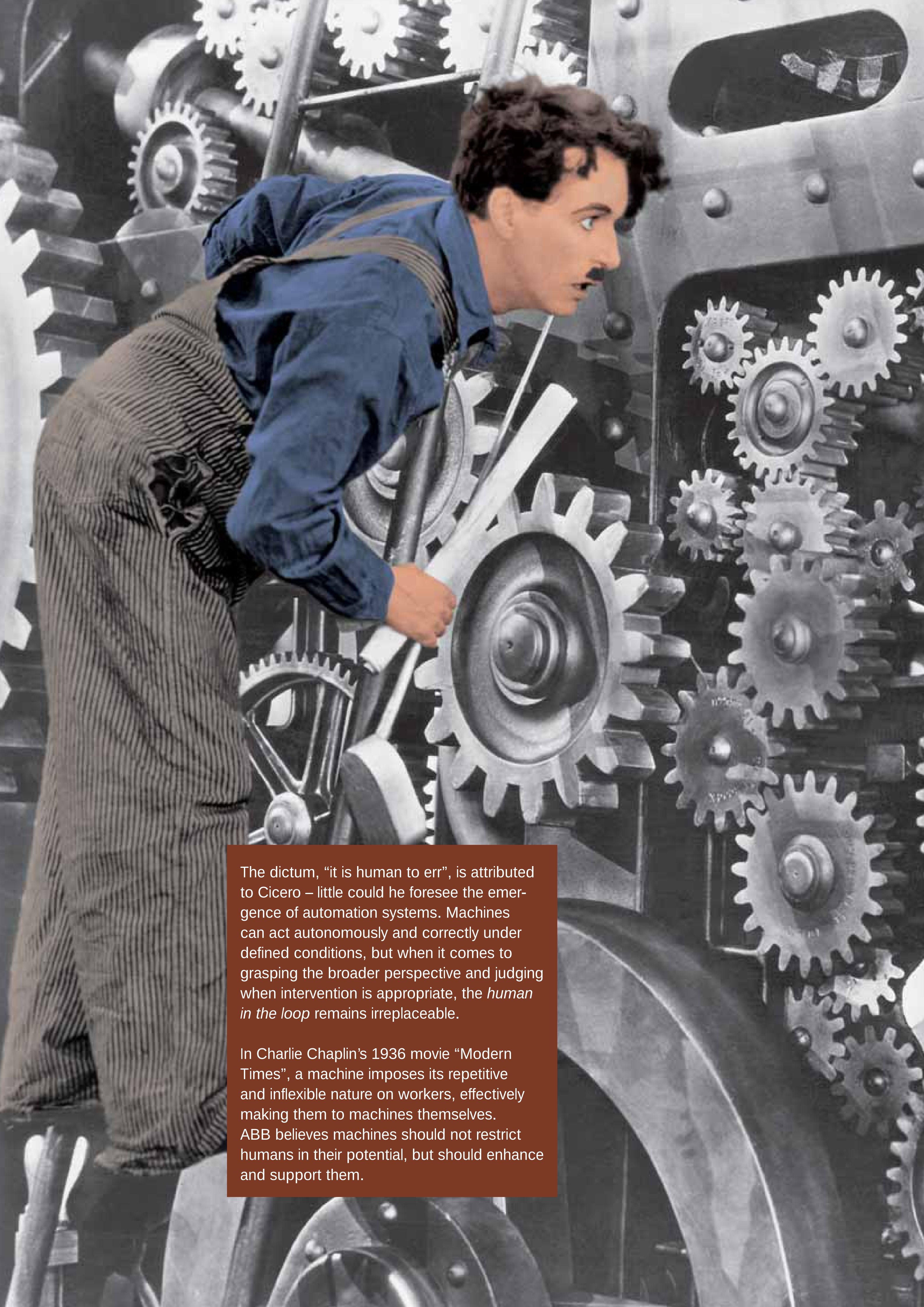

The dictum, “it is human to err”, is attributed to Cicero – little could he foresee the emergence of automation systems. Machines can act autonomously and correctly under defined conditions, but when it comes to grasping the broader perspective and judging when intervention is appropriate, the *human in the loop* remains irreplaceable.

In Charlie Chaplin’s 1936 movie “Modern Times”, a machine imposes its repetitive and inflexible nature on workers, effectively making them to machines themselves. ABB believes machines should not restrict humans in their potential, but should enhance and support them.



# Human in the loop

The global process industry loses $20 billion, or five percent of annual production, due to unscheduled downtime and poor quality. ARC[1] estimates that almost 80 percent of these losses are preventable and 40 percent are primarily the result of operator error. Blackouts in the power sector and meltdowns in nuclear plants are ominous words we have heard all too often during the last few decades. Rolling blackouts, resulting in heavy production losses within the affected region, give operators no chance to act because of the speed at which such disturbances propagate throughout an electrical network. The Three Mile Island accident in 1979 occurred because operators did not have all the information necessary to understand the real situation. The automation of industrial processes has evolved into large and sophisticated systems giving the operators structured and ergonomically presented information for decision support. No one would like to fly on a passenger jet without pilots. Hence the responsibility to oversee the safe and efficient performance of complex processes remains with the operators for now and the foreseeable future.

How then can we prevent productivity losses caused by operator errors, industrial explosions and blackouts due to hurricanes and other devastating events? By providing better and more accurate information to the human in charge in a form easily accessible for quick decision making. Issues concerning the *human in the loop* are now seriously researched and are at the top of the agenda in many businesses including ABB's. Exception management theories deal with the human issue related to long spells of inactivity with sudden burts of high level actions; a typical scenario for many operators including pilots. Ergonomics and information visualization, decision support and ease-of-use are all areas that have developed over the years in response to finding better ways to communicate between man and his machine. Academic research in behavioral sciences and practical experiences are being fused into solutions for the optimal support of the *human in the loop*.

In this issue of ABB Review we look at the research and development effort going on in these fields that are so vital to our portfolio of products and solutions. After a general overview of the science involved, this issue is organized into five sections; the first one of these, *Operational profitability*, is concerned with decision support. This section uses examples from the power sector (storm outages) and from process industries (electromagnetic stabilizers for galvanization). Smart alarming is a key research domain: Means are discussed of identifying and presenting only the most relevant alarms to the operator, permitting time-critical decisons to be based on the right information. A case study from the oil and gas industry is presented to illustrate this. Forecasting methods are needed to avoid unwanted events from occurring, especially if the propagation of such events is too fast for the human to act upon. A case study from Eastman Kodak is presented here to illustrate a possible solution.

The next section, *Capital productivity*, reviews visualization as the crucial vehicle in presenting information in ergonomic fashions for ease of comprehension. A lead-in article presents criteria adapted for system design with the *human in the loop*, and is followedby a number of articles describing how our own technology has advanced in this particular area. Examples from process and power industries are used. A look at how 3D graphics can enhance the understanding of the process information in the future is also included.

In the section on *Ease-of-use*, we explore the way in which drive technology from ABB epitomizes how the rapid development of ease of use in complex products can improve and broaden markets. Ambient intelligence is discussed in an article which also introduces the Smart&Lean product range from Busch Jaeger. Ease of use is also reflected in the development of tools permitting efficient identification of areas with improvement potential in plants, and also of tools for the enhancement of productivity in the engineering of substation standards. This section is concluded with the description of packaging technology in power semiconductors.

*Research activities* of academic nature or in cooperation with universities are exemplified in the next section, where an area of great interest is related to technologies for natural language querying of automation systems for different sets of information such as loop status and alarm inquiry. Professor on Drummond of Cambridge University, UK reviews how Augmented Reality can solve the issue of connecting the topological description of a plant with its real components – the binding problem as this is referred to.

The final section, *Perpetual pioneering*, introduces a series of historical articles covering the development of key ABB products over the last century. The initial historical overview presents the evolution our breaker technology has gone through since the early 20th century. We intend to present a historical review of a group of products in every issue in 2007 and 2008.

Enjoy your reading

Peter Terwiesch
Chief Technology Officer
ABB Ltd.

Footnote

[1] ARC Advisory Group, News 2006

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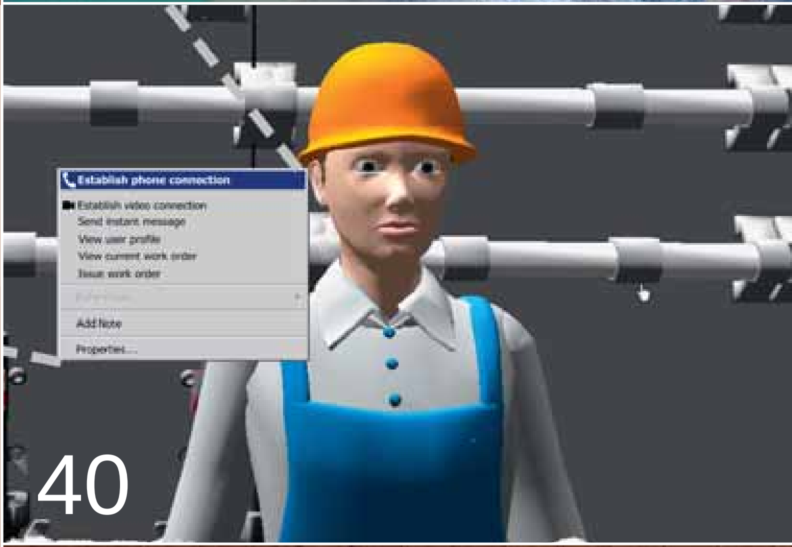
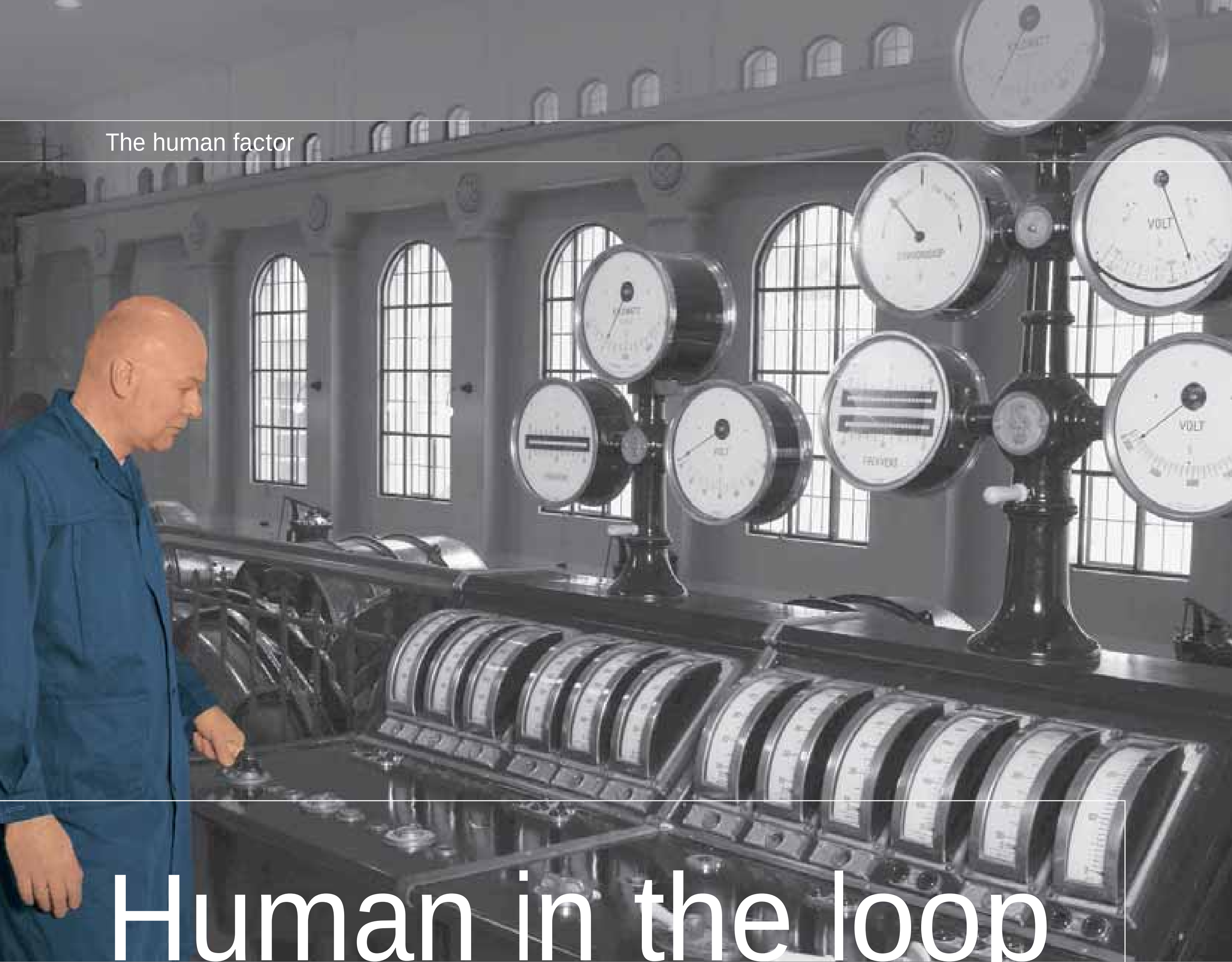



## Research activities




## Perpetual pioneering






# Human in the loop

## The human operator is a central figure in the design and operation of industrial automations systems

John Pretlove, Charlotte Skourup

Since the advent of computer control based industrial automation processes in the mid sixties, engineers have been continuously striving to minimize the discrepancies between a human's cognitive model of what he wants to accomplish and the control system's understanding of the task. Continued success comes in the form of improved system performance and safety, and greater reliability. Such improvements have resulted in the gradual elimination of the mundane tasks previously accomplished by operators, thus allowing the *human in the loop* to handle the more challenging tasks of supervision, exception control, optimization tasks and maintenance duties. Hence over the last 50 years a clear division of responsibilities between the human and the machine has evolved based on the optimal ability of each.

Maximising to the utmost this human-machine collaboration, however, depends on continued technology development in three major areas – decision support tools; ergonomics and visualization technologies; and ease-of-use of complex systems. The optimal synthesis of these three fields creates the state-of-the-art operator environment of modern automation systems.

Over the last fifty years or so, greater performance and improved reliability of industrial automation systems has relieved operators of tasks that are tedious, repetitive or hazardous. Instead, human operators in highly complex industrial automation systems such as electrical power networks, pulp and paper mills, power plants, and refineries now play a central role in tasks such as supervision, detection of abnormalities, maintenance, and process optimization. Despite the apparent paradox, it is clear that the human operator is an integral part of any automated control loop in almost all industrial applications of any size. Therefore understanding and maximising the collaboration between the control system and the human operator is essential. Adopting a systematic design approach is crucial for reasons of safety and optimum system performance.

### Humans as part of the automation system

In the early days of industrial automation, system designers attempted to automate everything and remove the human operator – whom they considered the weakest link in the process control loop – entirely. When this approach failed the human was assigned tasks the designer was unable to automate.

The skill sets associated with people as compared to machines were already well understood in the 1960s. The underlying principles were first described by Paul Fitts in 1951 [1]. Although his model was helpful in determining the allocation of functions between humans and machines, it did not consider the integration of both sets of skills nor how to improve the effectiveness of the human operator through computer system support and cooperation. Rather than eliminate people in industrial process automation, the trend nowadays is for substantial human involvement[1]. The reasons for this are:

- The degree of control in a process is a function of the predictability of process behavior and the degree of complexity. For all but the simplest of elements, it is not possible to model a plant fully or with sufficient explicitness. Nor is it possible to consider how external influences can affect the control system.
- Some processes could, from a technical point of view, be fully automated but the cost would be prohibitive. In any case, it is highly unlikely that the public would accept high-risk systems without humans taking overall responsibility. For example, the automation systems of a modern day passenger jet can handle both take-off and landing without pilot interaction. However, not many people would fly without a responsible pilot on board.

Important process characteristics that should be considered when designing a system with *humans in the loop* include:

- Process size and complexity
- The rate of change of the process
- The variability of the product schedule
- The process impact on the environment
- The economic cost of shutdowns
- The safety issue concerning people, equipment and the environment

**Understanding and maximising the collaboration between the control system and the human operator, and adopting a systematic design approach is crucial for optimum system performance.**

Humans are (largely) adept at dealing with the consequences of many of these factors. For example, they have the ability to recognise patterns and abnormal events based on large datasets, devise procedures to suit a new situation, store large amounts of knowledge for long periods of time, and reason and exercise judgement. To perform these tasks effectively, human operators have to be aware of the current situation at all times. They need the "right" information at the "right" time to be able to understand the current situation and to make the "right" decision. For this to happen, suitable visual support is needed. The most effective way of presenting large amounts of information so that the

1 A380 cockpit – courtesy Airbus

Footnote

[1] Dividing the labor between large, complex and dynamic industrial automation systems and knowledgeable human operators is one thing. The other more important thing is striking the right balance.

# The human factor

salient points can be quickly absorbed in critical situations has been researched within the field of cognitive science. In addition the disciplines of ergonomics and design must be properly applied to secure ease-of-use. The guinea pigs in these areas have been the cockpit of aircraft and the instrument panels of cars 1.

## Decision support

"Decision support systems are a class of computer-based information systems or knowledge-based systems that, in a very different manner, support decision making activities" [2].

An efficient decision support system for modern and complex industries needs to consider both the degree of automation and the human behavior. A significant part of most industrial processes are relatively straight forward to model and therefore to automate. On the other hand human behavior is much more complex, unpredictable and almost impossible to model. Instead of modeling the human (with a view to replacing him) the purpose of decision support in large automation systems is to add value to the human by assisting in the decision making process concerning a specific situation or an acute issue. It is however critical that the human operator remains in charge 2. The decision support system should not attempt to define what to do. Rather it should equip the user with enough information to enable him to fully comprehend an actual situation and predict the consequences of potential decisions. At the end of the day, it is the *human in the loop* who must decide on the best possible course of action.

A large plant with 10,000 loops or more would, under normal steady state conditions, perform for hours without any human interaction. The concern today is how to get the operator's attention when something abnormal and crucial suddenly happens. Again parallels can be drawn between the human reaction in this example and that of pilots in the airline industry. Intercontinental travel provides pilots with hours of no engagement. However if anything unusual happens, pilots are immediately jolted into action to quickly resolve any problems. This is one of the most critical issues of *human in the loop* systems. On the one hand the operator monitors the system but with few "hands-on" actions required. On the other hand when something deviates from the normal, the operator is expected to not only be fully aware of the (current and recent) state of the process, but he must also know what manual actions are required to handle the situation.

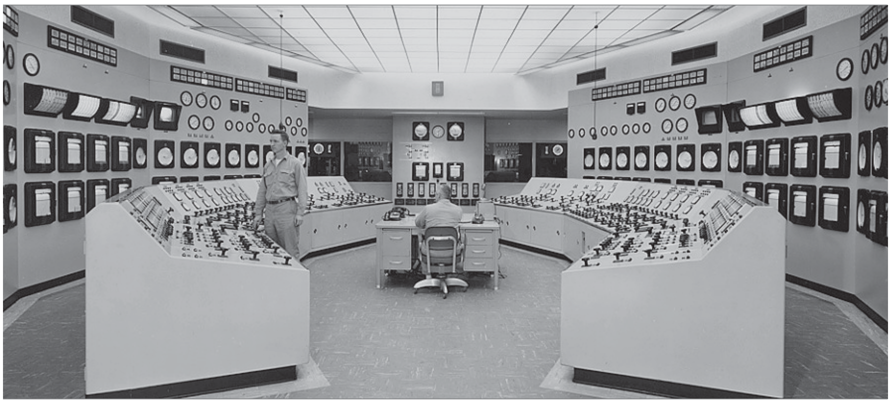
It is critical that the human operator remains in charge. The decision support system should not attempt to define what to do.

Research has shown that one very important area of support for the operator is how information is distilled and presented to provide an immediate and full overview of the situation. In a process plant environment for example, critical information such as:

- Initial alarms (but not the sequence of consequential alarms) should be easily and quickly identifiable.
- Performance data should be reduced into key statistical measures for quick assessment rather than displaying massive tables of data points.
- The current situation should be compared with previous and similar situations including previous actions taken to resolve the issue.
- The outcome or consequence of the operator's decision should first of all be predicted to enhance his chance of making the "right" decision.

Decision support can vary from direct recommendations, which the system provides automatically, to manually sought possibilities expressed in terms of trends, statistical information and alarm prioritization. For example, to support the operator in complex alarm handling situations, the alarms in the decision support software are filtered and color-coded to direct the operator's focus to the most important ones as the majority of them often represent follow-up alarms. Another example relates to root cause identification of a situation where alarms are assessed automatically and only the real cause of the problem is presented. It is becoming more common to provide case histories of similar occurrences including their resolutions, and the operator uses these cases to extend his internal repository of experiences.

2 A control room from the 1950s



## Ergonomics and information visualization

The word ergonomics comes from the Greek word "ergon" meaning work. When related to process automation it refers to the operating environment in which humans work. Variables in such an environment include the room size, the color settings, the furniture and of course the visualization of the information produced by the systems. Many studies have helped to define the minimum requirements for good operator performance, which include adjustable tables and chairs, screens with dedicated and overview information, defined color usage in displays and backgrounds, recommended methods when searching for information and parameter changes. These requirements must be clearly defined and consistently used throughout a system. Complications arise if several different systems are used in the same room, each with different ergonomic definitions. International Standards such as ISO 9241[2)] and 11064[3)], combined with industry best practice help to harmonize these systems, leading to improved overall efficiency.

## The control system is one of the main sources from which operators receive inputs reflecting the status of the industrial process.

Information visualization concerns how information is presented to the human operator. A more concise definition describes it as "a branch of computer graphics and user interface which are concerned with the presentation of interactive or animated digital images to users to understand data" [3].

The control system is one of the main sources from which operators receive inputs reflecting the status of the industrial process. Therefore, it is essential that information is presented in a way that allows the operator to thoroughly understand and comprehend the current situation. Since it is impossible to accurately model and predict human behavior, it is even more important to be aware of the power of correct presentation.

Information visualization incorporates a large range of different techniques, from conventional graphical user interface design to 3D/4D and virtual reality interfaces. Within the automation domain, information visualization covers everything from presenting (abstract) raw data on the operator screens and the interface design of human-machine interactions, to the special rooms equipped for remote collaboration. Traditionally, operator stations within the control room utilize piping and instrumentation diagrams (P&IDs)[4)] as an overview of the automated industrial process. Alarms are often presented in a separate system. However, redesigning the overview display to focus on and visualize changes in the process and combining it with alarms allows the operators to get an immediate picture of the relationship between changes and alarms. Such visualization may even prevent alarms from occurring since the operator will notice when the process is approaching the alarm limit. Spatial data visualization – such as a 3D model of the industrial process – is another way of presenting the operators with an overview of the system. Such visualization represents the geographical locations of equipment and the special interrelationships between such equipment. Furthermore, this 3D process model can integrate information from other systems to provide a complete single interface to several industrial processes or process segments.

### The design process: ease-of-use

"Ease-of-use refers to the property of a product or thing that a user can operate without having to overcome a steep learning curve. Things with high ease-of-use will be intuitive to the average user in the target market for the product. The term is often used as a goal during the design of a product, as well as being used for marketing purposes." [4].

The human operator is the key to success in the application of automation technology to process control. The collaboration between the *human in the loop* and the advanced industrial automation system depends on how easy it is to use the multi-faceted functionality of modern control systems. Sometimes, well over half of the control loops are manually operated because it is simply too complex

A modern and complex oil and gas process plant

Footnotes

2) Ergonomic requirements for office work with visual display terminals. ISO 9241 provides requirements and recommendations relating to the attributes of the hardware, software and environment that contribute to usability, and the ergonomic principles underlying them.

3) Ergonomic design of control centers. This eight part standard contains ergonomic principles, recommendations and guidelines.

4) A schematic type diagram showing the functional relationship between piping, equipment and instrumentation within process units in chemical plants, power plants, water treatment and similar plants. See http://en.wikipedia.org/wiki/Piping_and_instrumentation_diagram, retrieved 20 th October 2006.

3 Today's control systems have large-screen projections and individual operator workspaces

to tune the regulators for optimal performance. It is therefore essential to focus each aspect of the control system's capabilities onto the user and to design and develop the entire system with the human operator firmly at the center 3. The basic design principles [5] include:

- Organizing technology around the user's goals, tasks and abilities.
- Organizing technology around the way users process information and make decisions.
- Keeping the user in control and aware at all times of the state of the process through the technology.

Simplifying the steps needed to perform an action is crucial if the control system's capabilities are to be used effectively. Ease-of-use of a complex automation system starts with an in-depth understanding of the *human in the loop*. The designers must constantly and consistently understand the activities of the users whether they are supervisors, operators or maintenance engineers. Knowledge about human behavior helps to outline the basic architecture of the automation system based on the users' goals, tasks and expectations.

It is essential that the design of the entire automation system is such that any misinterpretation of data is completely avoided.

When an unexpected and unknown event occurs in the plant, the operator actively searches for information in order to get a picture of the process state. He is entirely dependent on and must trust the information which is accessible from the control system. Therefore it is essential that the design of the entire automation system is such that any misinterpretation of data, that could result in wrong actions and potential serious consequences for the industrial process and people onsite, is completely avoided.

## Summary

It is a common fallacy to think of automation as either fully manual or fully automatic. The situation is rarely so simplistic or so clear-cut. Instead the reality is that for most industrial automation systems a continuum of control ranging from fully manual to fully automated is adopted. There can also be different modes of operation which may be automated to different extents. Humans play a central role in modern industrial automation systems and their role in the future will be more important than ever before. The human operator also represents the most vulnerable element in the system and the one most easily overlooked. Understanding and optimizing the overall performance of industrial process control systems relies on a systematic and holistic approach, taking care both of the rapid development of technology and the special role that the human fulfills.

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[2] http://en.wikipedia.org/wiki/Decision_support_systems, retrieved 20th October 2006.
[3] http://en.wikipedia.org/wiki/Information_visualization, retrieved 20th October 2006.
[4] http://en.wikipedia.org/wiki/Ease_of_use, retrieved 20th October 2006.
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# The calm after the storm

## Human decision support in storm outage recovery

Rafael Ochoa, Amitava Sen

It's a fact of life that interruptions in an electrical distribution utility happen. Although they can be minimized, there are many times – especially during severe weather conditions or accidents – where they simply cannot be prevented. Whether high winds cause trees to fall onto overhead lines or poles to snap thus dislodging overhead lines from cross-arms, one thing is for certain: electrical service is disrupted until the physical facilities can be replaced or repaired, and this almost always involves human labor. The speed and efficiency at which these repairs can be carried out depends largely on the type of decision support systems or tools available to the distribution utility.

One such support system is known, in general, as an Outage Management System (OMS). With increasing requirements on utilities to track and report outages accurately, an OMS becomes a valuable and a necessary tool. ABB's Network Manager is an industry-leading OMS that has been deployed in numerous diverse electric utilities. This article looks at how this and similar tools help repair teams restore power as quickly and efficiently as possible.

Service interruptions can occur even when the weather is not so bad, such as heavy rain or strong winds. However, severe weather conditions such as hurricanes, ice and lightening storms have the potential to wreak havoc with electric utility transmission and distribution systems 1 and 2. While a distribution utility's goal is to restore service as quickly and safely as possible, severe storms can result in a massive number of customer outages that can take anywhere from days to weeks to repair, requiring hundreds or even thousands of field personnel. For example, large storms[1) such as tropical hurricanes, major snowstorms and ice storms have required up to two weeks of effort with a peak crew size of 10,000 to restore service to all customers. On top of this, total restoration costs have exceeded US$100 million for a single storm.

In most cases, the repair process begins with customer calls or with some indication of service interruption such as the operation of automated devices. Typically in some countries, distribution networks do not have extensive remote field monitoring or control and often the only way a distribution utility knows a problem exists with the system is when a customer calls to report an outage. The OMS collects (ie, analyzes) a set of outage calls, and from the pattern of calls received it can determine the likely location and a possible cause of the outage. A crew is sent to the location of the outage to investigate further and make repairs.

1 Severe ice or frost can play havoc with power lines

2 Hurricane Damage to electricity poles

**The best possible decision support tools or systems are required to restore power quickly and efficiently subject to the most stringent safety standards.**

Prior to the introduction of computerized systems, the telephone calls received by the utility were either written up by hand on a "ticket" or entered into a computer and then printed. These tickets were manually sorted based on the circuit the customer was connected to, before being analyzed to (a) determine the electrical location of each customer associated with the ticket and (b) attempt to identify the root cause of the outage. This process may work well in day-to-day operations where the volume of calls is light and the number of outages is small and if the expertise is available in house. However, a paper-based system easily becomes overwhelmed during large storms where more than a million customer telephone calls may be generated. Also, as experienced labor retires, this expertise is no longer available.

Apart from the physical damage, the damage caused by large storms has a severe social impact. The human effort needed to carry out repairs requires the best possible decision support tools or systems that allow power to be restored as quickly and efficiently as possible subject to the most stringent safety standards.

### Outage Management Systems

One such system is an Outage Management System (OMS). Utilities typically have an OMS to help log customer calls Factbox 1 and dispatch crews to the source of an outage. To be as effective as possible, an OMS requires an accurate and complete connectivity model, from the distribution substation breaker right down to the customer transformer. The low voltage

Footnotes

[1)] The destruction caused by catastrophic events such as Hurricane Katrina in the US in 2005 is not included.

[2)] For more detailed information, please refer to www.abb.com/industries/seitp408/1592686e90c27d6ac1257026003981d2.aspx – November 2006.

**Factbox 1 Outage Management System – an overview**

An Outage Management System (OMS) provides the capability to efficiently collect, identify and resolve outages and generate and report valuable historical information. The OMS accepts inputs such as customer phone calls, SCADA telemetry data, automated meter reading inputs and other real-time data and determines the likely locations of the equipment failure or damage that has caused the current set of outages. This analysis substantially reduces the need for humans to patrol distribution feeders to locate the root causes of outages. Furthermore, the OMS can automatically create, dispatch and keep track of repair crews, and it provides software tools to secure their safety as they work. Graphical tools in the system allow distribution control room operators to visualize the state of the network, the pattern of incoming calls, confirmed outages, and the planned location and tasks of the restoration crews. It can interface with mobile crew dispatch systems to keep track of and communicate with mobile crews. The OMS also provides a collection of advanced analytical tools – such as load flow and short circuit calculations, fault location and restoration analysis – that allow the utility to create efficient restoration plans and calculate Estimated Time to Restore (ETR). With these the utility can provide regular updates to the customer of the outage situation and restoration status.

side is usually not modeled in the interests of reducing the overall network model size and the cost-effectiveness of collecting and maintaining this level of detailed data.

An OMS is characterized by a graphical user interface (GUI) that can display from one to several feeders at the same time. The entire distribution system, known as a "world map", can also be shown in a single display. ABB's Network Manager DMS[2)] is an industry-leading OMS and a typical graphical display is shown in 3.

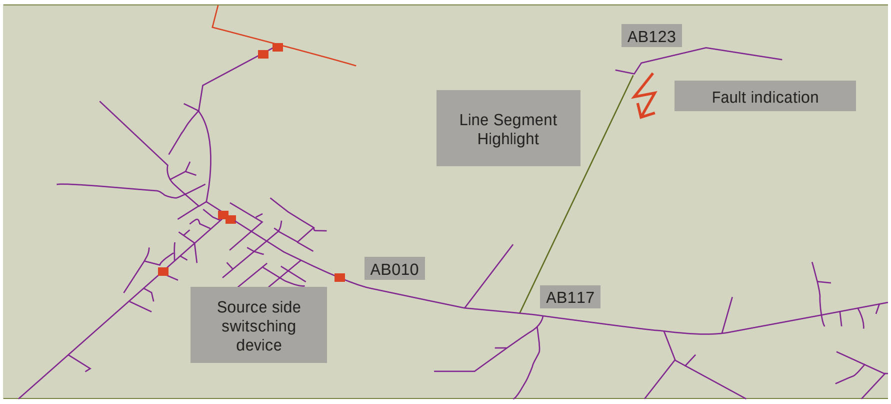
## An Outage Management System provides the capability to efficiently collect, identify and resolve outages and generate and report valuable historical information.

The primary real-time inputs to the OMS are the trouble calls from customers or emergency personnel as well as indications from automated devices such as those controlled by systems typically known as Supervisory and Control Acquisition Systems (ie, SCADA). The OMS is capable of receiving anywhere from a single call to a very large volume of calls Factbox 2 which it then analyzes and groups together to form something that is easier to handle. The grouped calls are transformed into what is referred to as an outage and sent onto the GUI that

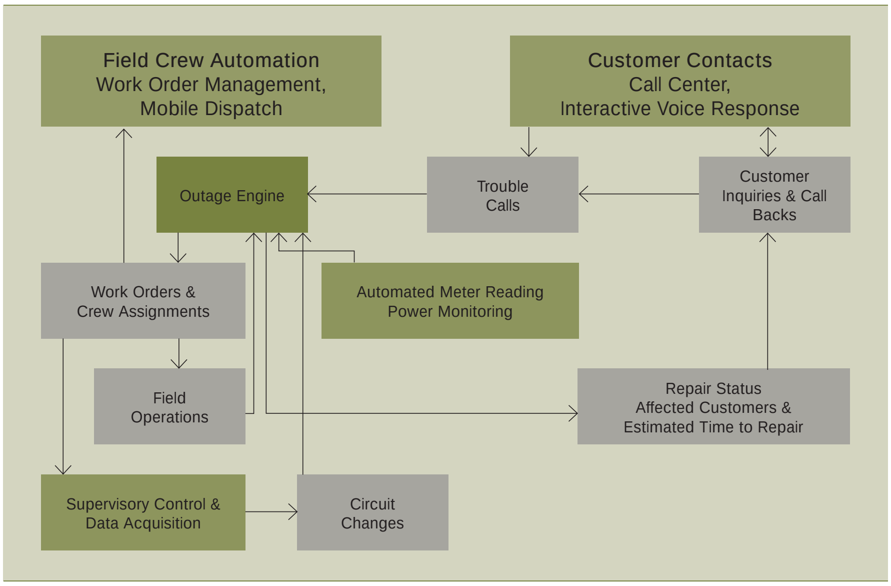
**Factbox 2** How to deal with large volumes of trouble calls

Trouble call volumes that were a rare problem only a few years ago are now commonplace. An OMS typically works in conjunction with automated call-taking/handling system typically referred to as an Interactive Voice Response (IVR) system. These systems can be further supported by third-party high call-volume systems for an overflow condition that overwhelms the utility call-taking system. One such third-party vendor is capable of taking millions of calls per hour.

3 Graphical user interface for outage management




4 The basic work flow for managing outages




presents not only the location of the individual calls, but more importantly, the results of the analysis. Although a dispatcher handling the outages may want to display only outages as opposed to individual calls, the OMS can also display large call volumes in a geographic display in real-time, while at the same time providing the same information simultaneously to a large number of utility employees.

The basic work flow diagram for managing outages is shown in 4. The *Outage Engine* lies at the core of the OMS and comprises the *Trouble Call* and *Outage Analysis* functions, and the associated crew dispatch tools. It identifies customers with outages and then assigns, dispatches and follows the crew process until power is restored. The Outage Engine continuously analyzes the "as-operated" electrical network to define outages and keeps track of customers without power.

Characteristically in distribution systems it is difficult to maintain up-to-date knowledge of the "as-operated" network given its very dynamic, ever changing nature. The "as-operated" network may be very different to the "as-designed" or to the "as-built" network. Information about the "as-designed" and "as-built" network may be available from other utility IT systems such as Geographic Information Systems. If, however, a safe and efficient outage restoration is to be achieved, the current state of the network must be continuously maintained by the

## Operational profitability

software with the best telemetry and manual/voice inputs available.

Unlike transmission systems, a problem peculiar to distribution networks is the ability to add temporary devices, such as line cuts and jumper lines. Such temporary devices are uncommon in transmission systems, but are very common in distribution systems. Since most distribution systems run in a radial configuration, it is often necessary to operate feeder tie switches to reconfigure feeders, either to restore outages or to adjust to different loading situations. There is a need then to be able to (a) dynamically color lines according to the direction they are being energized from and (b) to color lines according to whether they are energized or not. Another characteristic of a distribution system is that change is the norm. For example, new residential developments, expanding towns and cities, and routine maintenance means that the distribution network model changes frequently. It is not uncommon for 10,000 or even 100,000 changes to occur in a single week! The ability to apply such changes incrementally while the software is up and running is a necessity.

### Storm recovery

Distribution outage situations can be classified according to the scope of the damage and the number of customers impacted.

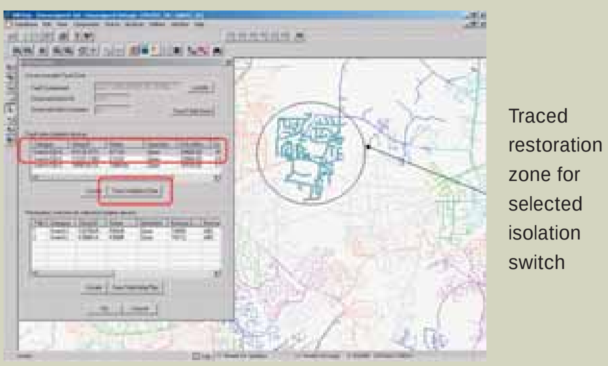
- Normal day-to-day outages due to minor storms, animal contact, and broken tree branches for example sit at the lowest level. These are usually handled locally through conventional outage management processes.
- The next level concerns outages that are caused by localized storms impacting a small area, damaging poles or primary equipment within an operating area and requiring more line crews than are normally scheduled. In cases where severe storms have impacted a wider area within the same operating area, extra "outside" resources may be required particularly if multiple feeders suffer mechanical damage.
- The second highest outage level is reserved for storms that impact multiple operating areas and where more than 10 percent of customers may be without power. In these situations resources from other utility operating regions need to be called in.
- At the highest impact level, centralized storm management is needed after a severe storm to coordinate both internal crews and extra resources called in from other utilities or contracting agencies.

The work of restoring power effectively begins before a major storm has struck. The utility typically performs an assessment of the amount of damage it thinks may occur and where. Crews are then dispatched to staging areas to be in position to make repairs once the storm hits. When this eventually happens, the utility starts to receive damage assessment reports from survey teams in the field. This information pinpoints what portions of the circuit have been damaged and to where the dispatch maintenance crews must go. An example of the restoration support tool is shown in 5. It is highly likely that in a severe storm situation, all OMS decision support tools and services described in Factbox 1 are brought into play.

**In a distribution system, change is the norm. It is not uncommon for 10,000 or even 100,000 changes to occur in a single week!**

Two of these services, however, merit further elaboration. The first deals with the need to handle extraordinary restoration processes with a larger number of crews than usual. *Dispatch and Crew Administration* modules provide web-based capabilities to manage work orders and administer crew personnel, vehicles and equipment not only from the central control room but also from service centers or specially created "storm room" operations. Under normal conditions the distribution system is typically managed from a central control room, which is responsible for all routine switching together with a number of dispersed service centers, which might dispatch crews locally under the coordination of the central control room. In the normal configuration it is likely that users of the OMS in the service centers have less authority than cen-

5 A screen-shot taken from the restoration support tool




6 A temporal trend display provides call and outage trends on a system or district basis over any defined time period

tral control room personnel. However, because of the massive increase in workload in a severe storm situation, the central control room may delegate much higher levels of switching and crew dispatch authority to the service centers, thus allowing it to concentrate on dealing with high level coordination and planning tasks plus switching actions on major network backbone elements. An extremely flexible and dynamically adjustable user authority scheme forms the basis for this capability. Each user logs in with a specific user role and area of responsibility. The user role is based on responsibilities and qualifications. Areas of responsibility define operating boundaries for each user, from a single device to a specified geography (eg, group of postal codes) or a predefined segment of the network, for example a group of feeders. These user roles and areas of responsibility may be pre-defined or easily adapted by a system administrator to permit a flexible and coordinated storm response from the service centers and the central control room.

## As the frequency at which large tropical storms occur is on the upswing, improving damage prediction is fast becoming a necessity.

The second service deals with the need to provide accurate and timely information to all appropriate utility employees, including the central managers responsible for informing the public. A suite of web based applications in the OMS permit authorized users across the enterprise to view, query and act upon outage and operational information. Users need only an internet browser and appropriate access authority to use these tools. Among these applications, an *Executive Information module* provides a global view of the situation including summaries by district. Users can access sub-levels if detailed information is required. The summary data will typically include the number of outages, the number of hazardous outages, total customers without power, total critical customers without power, cumulative hours of total outages, maximum outage duration, number of calls received, number of crews available and assigned, etc. A temporal trend display is available to provide call and outage trends on a system or district basis over any defined time period 6.

### The future

Upgrades and improvements are an inherent part of any software-based tool or system. However, as the frequency at which large tropical storms occur is on the upswing, many improvements may be needed sooner rather than later. Improving damage prediction is perhaps a sensible place to begin as severe weather in the form of hurricanes and ice storms continue to plague large areas of the inhabited world. By better forecasting the amount of damage a storm will cause, the resources required for restoration and the time needed to restore service to customers, a utility can effectively plan a way of getting resources quickly into place or on stand-by.

Storm damage prediction is based on an accurate weather forecast of variables related to distribution circuit damage. Taking ice storms as an example, a typical variable could be the amount of ice accumulation on trees surrounding overhead lines or on overhead equipment itself. Wind speeds and gust durations could be two variables associated with hurricanes. In any case, expected damage can be predicted based on historical information and susceptibility models, and this estimate would then allow crew requirements to be directly computed.

The OMS circuit models can be extended to analyze the relationship between crew allocation, predicted and verified damage as well as to calculate Estimated Time to Restore, ETR. During the restoration process, managers can not only use calculations based on these extended models to look at the trade-off between adding more resources and any resulting improvement in customer restoration times, but also to find the most cost effective use of the resources available.

## By better forecasting the amount of damage a storm will cause, the resources required for restoration and the time needed to restore service to customers, a utility can effectively plan a way of getting resources quickly into place or on stand-by.

Future enhancements in storm outage management are discussed in greater detail in [1].

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# Galvanizing support

## An electromagnetic strip stabilizer to optimize zinc coating

Peter Lofgren, Mats Molander, Olof Sjodén

In the exacting process of galvanization, any movement of the steel strip outside the expected path can lead to problems. If it moves relative to the air-knife that removes excess zinc, the coating will become uneven and may fail to meet quality requirements. Strip movement may also damage surrounding installations. To address this problem, ABB has developed an electromagnetic stabilizer that can reduce vibrations and oscillations at the air-knife, without touching the strip. This solution provides better control of the coating process, leading to improved product quality and faster line speeds. The more even coating also provides cost savings through reductions in the amount of coating material used.

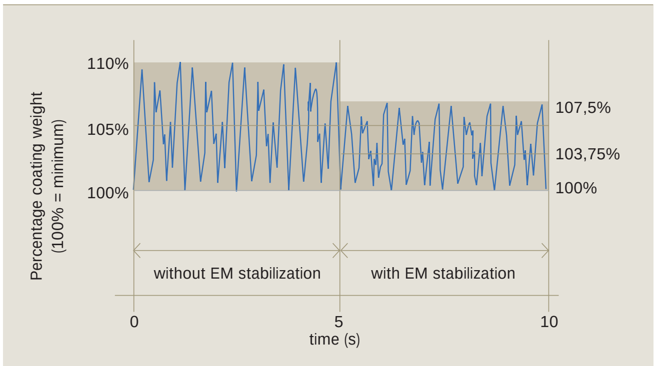
Following successful trials of the equipment at SSAB Tunnplåt AB in Sweden [1], the first electromagnetic stabilizer for a modern, high-speed, ferromagnetic-steel galvanizing line has now been installed and tested at Thyssen Krupp Stahl in Germany, with impressive results. The ABB EM Stabilizer was launched on the market in October 2006.

At the heart of a galvanizing line is the zinc pot – the area in which the steel strip is coated with a thin layer of zinc to protect it from corrosion. Everyday, operators are faced with the challenge of meeting quality requirements within specified cost-margins, while keeping up with production quotas. Apply too little zinc and the steel will be inadequately protected, apply too much and the costs will spiral.

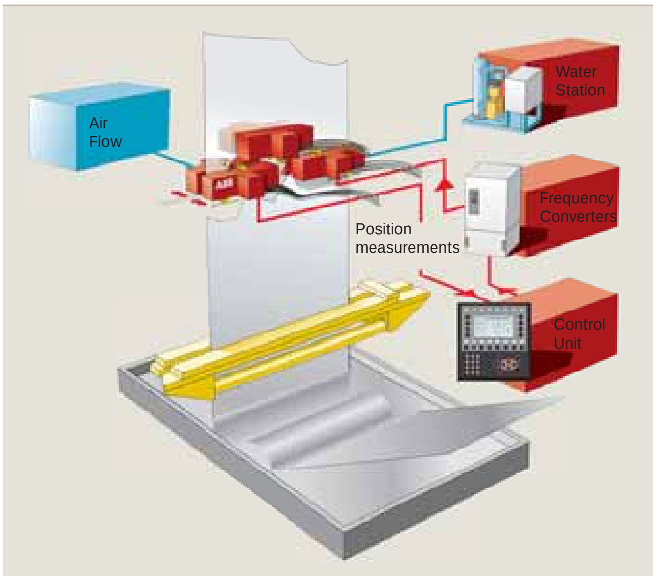
Quality is heavily dependent on the level of vibration in the strip because excess zinc is removed by the action of an air-knife. Until now, there was neither a means of measuring this vibration, nor any way of dampening it. Operators had to rely on visual inspection of the strip surface and down-stream measurements of the zinc coating. If quality was found to be poor, the only solution was to slow production – an unpopular measure in any industry.

The ABB Electromagnetic (EM) Stabilizer offers another solution. It is capable not only of monitoring vibration levels in the steel strip, but also of dampening and maintaining them at a consistently low level.

1 Schematic graph showing the variation in weight of zinc coating with (right) and without (left) EM stabilization. A reduction in variation from 10 percent to 7.5 percent, reducing the average coating (red line) from 105 percent to 103.75 percent of the minimum (green line), leads to a potential saving of 1.25 percent zinc used.




2 The ABB EM Stabilizer system




### Benefits of vibration control

Reducing strip vibration improves the control of the air-knife action, making the final coating more uniform. This improved consistency means that the initial application of zinc can be reduced, helping steel users to optimize their products with respect to cost, weight and quality.

Most of the vibration in galvanizing lines arises from a small number of sources. These are imperfections in the line's mechanical components, from the long, free, unsupported strip path, the air blowers, and from the shape and properties of the strip itself. The impact of these factors can be controlled to some extent by regular monitoring and maintenance of critical components and parameters eg, roll bearings and end-roller alignment. But vibrations cannot be eliminated completely, and they are accentuated at higher line speeds and on longer unsupported strip paths.

The benefits of the ABB EM Stabilizer can be summarized as follows:

- Improved product quality resulting from a more even coating
- Increased line speed with maintained or improved coating quality
- Quieter work environment: The reduction of strip vibrations allows the knife to be placed closer to the strip, thus requiring a lower air pressure and hence reduced noise level.
- Cost savings: Additional zinc coating, required to accommodate strip vibration, is in the range of 5–15 g/m² and accounts for 5–10 percent of the process zinc consumption. Since zinc is expensive, even a slight reduction in usage will quickly compensate for the cost of the ABB EM Stabilizer.

The example in 1 illustrates how zinc saving can be achieved by reducing strip vibration. The left-hand part of the figure shows the process without stabilization and the right-hand part with stabilization. Without EM stabilization, a zinc margin of 5 percent is used, ie the average coating weight is 105 percent of that specified. This margin is chosen so that, despite variation in the coating weight (here, 105 ± 5 percent), at no point will the zinc layer be less than the specified thickness (100 percent). By reducing vibration, variations in the zinc coating are reduced from ± 5 percent to ± 3.75 percent. This allows the set point to be reduced from 105 percent to 103.75 percent, without the risk of falling below the stipulated coating weight. Hence, a total zinc saving of 1.25 percent is achieved. This equates to a 25-percent reduction in wasted zinc.

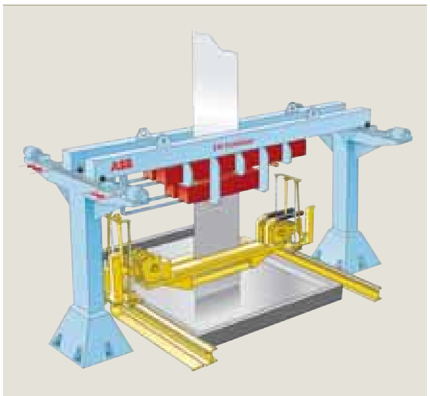
### The ABB EM Stabilizer system

#### Equipment

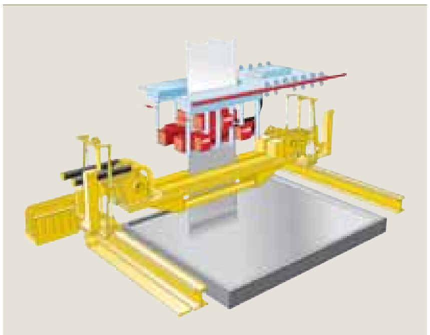
The main components of the ABB EM Stabilizer are six electromagnets, a water-cooling station and a cubicle, containing three frequency converters and a PLC (programmable logic controller). The frequency converters each control the currents to one pair of electromagnets. The stabilizer is also equipped with several air-cooled position sensors to detect the strip position as a function of both time and space. The stabilizer is operated from

## Operational profitability

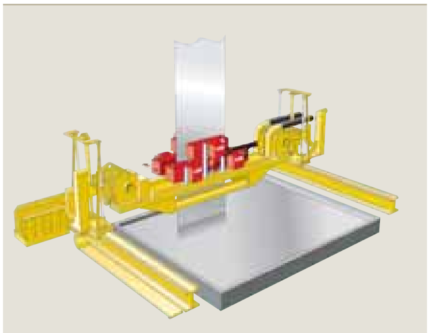
3 The ABB EM Stabilizer installed on a beam supported by two pillars



4 The stabilizer suspended from an overhead construction



5 The stabilizer installed close to air-knife



6 Hot Gauge platform with ABB EM Stabilizer magnets

the PLC panel with alarm handling and operation control 2.

Each electromagnet consists of an iron core with electric windings. The windings are series-connected and cooled by water. The magnet sections are enclosed in a stainless steel casing and are positioned in pairs to control for three-dimensional movement in the strip. One magnet from each pair is mounted at the front of the strip, with the other mounted at the back. Two pairs are arranged so that they cover the left- and the right-hand sides of the strip, and the third pair is located above or below the other two pairs. Position sensors are mounted on a guide in between the two magnet levels. The side magnets work together to remove left-right vibrations (twisting) and first mode oscillations (ie string mode). The central magnets compensate for static deformations of the strip, typically cross-bows, but also to remove the flapping mode of oscillations.

> This improved consistency means that the initial application of zinc can be reduced, helping steel users to optimize their products with respect to cost, weight and quality.

### Function

The ABB EM Stabilizer functions by exploiting the magnetic properties of ferromagnetic steel; it applies three “semi”-static magnetic fields to control the moving strip. The position sensors measure the discrepancy between the strip path and the optimum path line and feed these data to the PLC. Typical strip vibrations are in the range of 1–10 Hz; however, the control algorithm needs to be much faster than this to achieve dampening.

### Installation

The mechanical mounting of the magnets is tailored to the line in question. Conceptual layouts for the installation of the ABB EM Stabilizer above the air-knife are shown in 3 and 4. The installation method in 3 was used in the first trials at SSAB Tunnplåt AB in Sweden.

To achieve maximum vibration dampening at the air-knife nozzles, the magnets should be located close to the air knife, as shown in 5. If the magnets cannot be positioned close to the air-knife, they can be suspended from the overhead construction, as shown in 4. Here, the lower magnets are approximately 1.8 m from the air-knife. This installation method was used at Thyssen Krupp Stahl (TKS) in Germany, to meet the criteria shown in the Factbox. One half of the ABB EM Stabilizer, suspended from the hot gauge platform, can be seen in 6.

### Results

The effect of the ABB EM Stabilizer was evaluated by comparing vibration levels and variations in the thickness of the zinc coating, with and without the use of the stabilizer. The stabilizer was tested on a variety of strips (eg galvannealed/galvanized, exposed/unexposed, thin/thick, narrow/wide) and line parameters (eg thin/thick coating, fast/slow strip speeds, high/low strip tensions). All evaluations were made on individual coils, one half of which was subject to EM stabilization, the other not. Whether the first or second half of the strip was stabilized was varied at random.

Variations in coating weight were measured using a cold gauge (ie measurements are taken after the strip has cooled), and strip vibrations, both with and without stabilization, were measured using either the sensors of the ABB EM Stabilizer or mobile sensors mounted on the air-knife beam.

Results presented here are typical of those obtained and can be considered

**Factbox** Line data TKS GL #4

| | |
|---|---|
| Qualities produced | Exposed/unexposed automotive, galvanized/galvannealed |
| Line Speed | Up to 180 m/min |
| Width | 1100–2040 mm |
| Thickness range | 0.6–1.6 mm |
| Yearly production | 500,000 ton |

## Operational profitability

as average results over the coils that were stabilized.

### Vibrations and zinc variations

Typical strip vibrations, with and without stabilization, are presented in 7. Stabilization typically reduced vibrations by a factor of two or more. It also reduced low frequency movements of the strip ("snaking", with a period of several minutes).

The potential for saving zinc by strip stabilization was investigated in great detail. 8 shows the distribution of zinc coating weight, with and without stabilization. The ABB EM Stabilizer reduces the variation of coating weight significantly, leading to a reduction in the over-coating margin of 25 percent (from 4 g/m² zinc to 3 g/m²) and an overall saving of two percent.

### Other observations

ABB EM Stabilizer was installed on a TKS automotive line. This line produces a lot of exposed material, and hence extremely high quality surfaces are required. Because of this, the stabilizer could not be allowed to adversely affect the surface in any way. During these tests:

- no negative effect on the surface quality was detected, either by visual inspection or the use of stone tests[1).
- the distance between the magnets on each side of the strip was shown to be sufficient.

Results also confirmed that the ABB EM Stabilizer is well suited to the tough industrial environment of the zinc pot. It can tolerate the presence of zinc dust and temperatures rising to 100 °C.

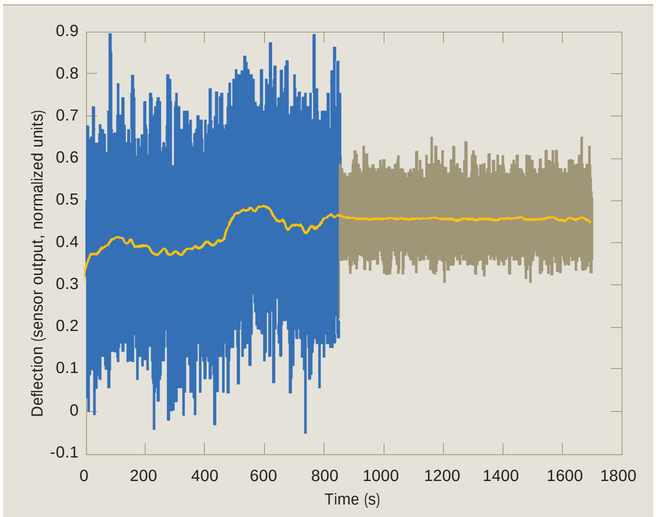
The current positioning of the stabilizer, approximately 1.8 m from the air-knife, produced significant results. Further performance improvements are expected from installations that are positioned closer to the knife.

**The ABB EM Stabilizer reduces the variation of coating weight significantly, leading to a reduction in the over-coating margin of 25 percent (from 4 g/m² zinc to 3 g/m²) and an overall saving of two percent.**

### In summary

The installation of the ABB EM Stabilizer on a galvanizing line at TKS in Germany has demonstrated the benefits of reducing vibration and snaking of steel strips during galvanization. Results from a substantial number of coils showed that significant improvements in terms of cost savings and improved product quality can be made with no adverse effects being recorded. These improvements were seen with the stabilizer installed approximately 1.8 m away from the air-knife. Further improvements would be expected from installations closer to the knife, where the stabilizing effect would be enhanced. The ABB EM Stabilizer was launched at the Galvanizers' Association meeting in Columbus, OH in October 2006.

7 Typical strip vibrations without (blue) and with (red) stabilization

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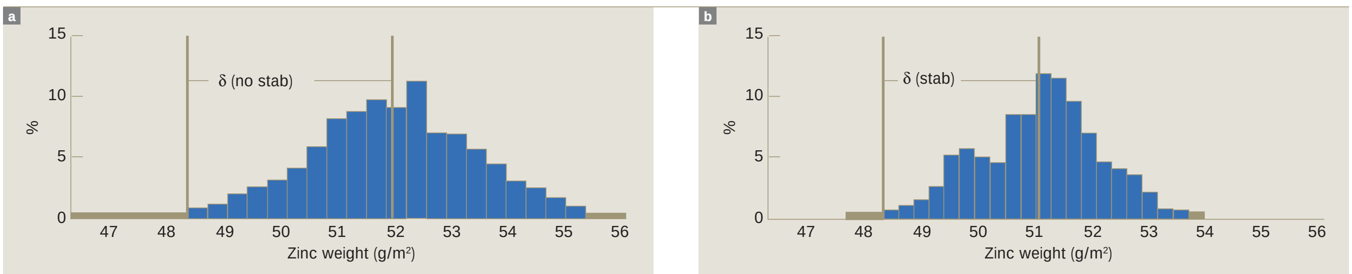
Footnote

1) The stone test is a flatness test whereby a flat soft sand stone is run along a surface. If the surface is not sufficiently flat, the intensity of the resulting scratches varies visibly.

Reference

[1] Olof Sjöden, Peter Löfgren, Hans Sollander, Mats Molander, 2005 "Stabilizing influence, No-contact vibration control of steel strips in galvanization". ABB Review, 4/2005

8 Typical coating weight distribution without a and with b stabilization and potential zinc saving δ (no stab)-δ (stab). b has been adjusted for a possible decrease in zinc coating set point. (99 percent of the values are captured by the green bars, ie only 0.5 percent of the values are allowed to be larger or smaller.)



# Intelligent alarming

## Effective alarm management improves safety, fault diagnosis and quality control

Martin Hollender, Carsten Beuthel

Courtesy Chilten Air Support Unit, England

As industrial plants become larger and more complex, an increasingly sophisticated alarm system is required to inform operators of potential malfunctions. With hundreds of different processes running at once, operators can be hard pushed to keep up with alarms, even under normal conditions. Without careful management, alarms can be ignored by even the most diligent of operators. Persistently active alarms may even be disabled, leading to potentially disastrous consequences.

To ease the problem of operator overload, ABB offers a number of alarm management tools. Its Power Generation Information Management (PGIM) system incorporates alarm and event management functions, and the alarm hiding functions of System 800xA allow certain alarms to be hidden under certain conditions, thereby avoiding unnecessary distraction of operators. ABB Engineering Services, together with local ABB project groups, also provide alarm management consulting services.

With modern digital control systems (DCS), it has become very easy to configure large numbers of isolated alarms. This often results in systems that generate many alarms (more than 2000 alarms per day and operator are typical for many industrial processing plants) during normal operation, and even more during process upsets. It is unreasonable to expect an operator to respond to alarms arriving at this rate.

In the oil and gas industry, alarm management is a well-established practice and, in many cases, a legal requirement. Other industries, such as power generation, pulp and paper, and the chemicals industry, are following suit. In 1999, the Engineering Equipment and Materials Users Association (EEMUA) published a guide to the design, management and procurement of alarm systems, known as EEMUA 191 [1]. The document has since become the worldwide de facto standard for alarm management. Among its key messages are that every alarm should be useful and relevant to the operator, and that operators can be realistically expected to deal with a long therm average alarm rate in steady operation of around one alarm every 10 minutes. It also states that all alarms should have predefined operator responses.

The basic recommendations [2] for alarm management are to:

- Measure alarm rates, and other alarm key performance indicators, and compare them with recommendations from EEMUA 191, or with values from reference plants.
- Identify low hanging fruits – it is often possible to improve an alarm system significantly with very little effort.
- Eliminate nuisance alarms. This might include tuning control loops, replacing faulty sensors and changing the status of some indicators from alarms to events.
- Measure the alarm performance indicators regularly to ensure they stay in the desired target area.

These cost-effective steps relate to normal operating conditions. Once they are well under control, the next step is to reduce alarm floods during process upsets.

### Current situation

In the control rooms of many existing plants, one can easily find symptoms of bad alarm management. These include:

- Display screens persistently covered with alarms
- Frequent alarms during normal operation, and even more during plant upsets
- Alarms standing for long periods (days or weeks)
- Bulk acknowledgement of alarms without investigation ("blind" acknowledgment)
- Operators failing to value alarms as a support system
- Audible alarms being disabled to avoid constant noise pollution

**In Milford Haven, the operators (a team of two) received 275 different alarms in the 11 minutes before the explosion.**

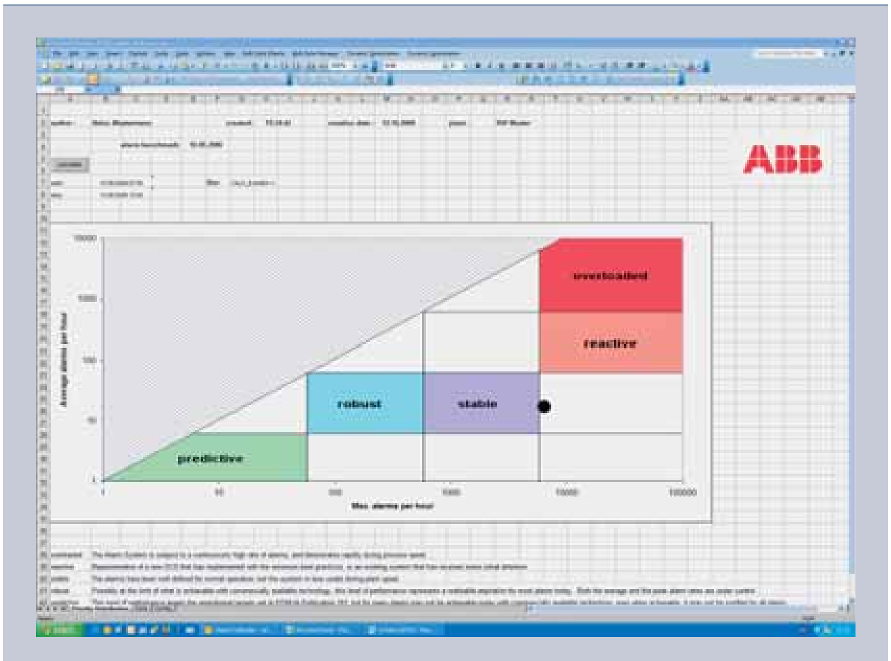
In extreme cases, the alarm system is completely ignored by the operators and the plant would run more efficiently if the DCS had no configured alarms at all!

In large safety-critical plants such as refineries or offshore platforms, alarm management is often required by law. A thorough analysis of accidents like the Texaco Refinery explosion at Milford Haven (1994) has clearly shown that bad alarm management contributes to accidents: In Milford Haven, the operators (a team of two) received 275 different alarms in the 11 minutes before the explosion. This is why a number of authorities, including the UK's Health and Safety Executive and the Norwegian Petroleum Directorate [3], require safety-critical plants to implement systematic alarm management.

If critical situations can be stabilized and emergency shutdowns avoided, this not only increases the safety of a plant, but also offers substantial economic benefits – unplanned shutdowns are very expensive and better alarm management enhances process efficiency.

EEMUA 191 is a set of guidelines for alarm management, but its recommendations are not mandatory. However, the document does describe best practice and is used by a number of regulatory bodies. Standards such as Namur NA102 "Alarm Management" [4] and ISA RP18.2 "Management of Alarm Systems for the Process Indus-

1 Alarm management benchmark, first proposed by Campbell Brown of British Petroleum



## Operational profitability

tries" [7] are based on the ideas in EEMUA 191. The guidelines focus on the properties of the operator's information processing capabilities and emphasize the usability of alarm systems from the operator's perspective. The old way of thinking was to blame malfunctions on human error if an operator had overlooked an important alarm. However, EEMUA 191 makes it clear that if the plant's management has failed to reduce alarm rates to a reasonable level, then the operator cannot be held accountable.

EEMUA 191 specifies several measurable performance indicators that can be used to assess the performance of a plant's alarm system:

- The long term average alarm rate in steady operation should be less than one alarm in 10 minutes.
- The number of alarms during the first 10 minutes of a major plant upset should be less than ten.
- The recommended alarm priority distribution is high (5 percent), medium (15 percent), and low (80 percent).
- The average number of standing alarms should be less than ten.

EEMUA 191 offers an affordable methodology to compare practices in individual plants with industry best practice.

### Alarm management basics

An important first step in alarm management is to record all A&E (alarms and events) messages in an electronic database for further analysis. Alarm printers are still used in some plants, but they are expensive to maintain and can result in valuable information being buried in archives that nobody reads. Alarm management tools, like Power Generation Information Management (PGIM), can connect to all kinds of different DCSs, for example with help of the OPC[1)] A&E standard, or by using a printer port. PGIM allows A&E messages that are stored in SQL[2)] server databases to be searched and filtered.

The old way of thinking was to blame malfunctions on human error if an operator had overlooked an important alarm.

The following steps are typical of an alarm management project (see eg [6] for a detailed description):

### Benchmark

Once a significant quantity of data has been collected from a plant, it can be compared with reference plant data eg, as provided in EEMUA 191. Subsequent strategies can be devised according to certain key performance indicators 1.

### Alarm philosophy development

It is very important to have a single written document that describes a consistent, plant-wide, alarm philosophy. This document must define the methodology and rules for setting alarms, eg how alarms should be prioritized. It must describe operators' roles and responsibilities and how changes in current practice should be managed. Such a document may already exist as part of the plant's engineering strategy. If not, it must be created as part of the alarm management project.

### Nuisance alarm removal

Nuisance alarms are alarms that serve no justifiable purpose, ie they are of no value to the operator. Such alarms exist in many plants and their removal can reduce the alarm rate significantly with very little effort. A very useful tool for the identification of nuisance alarms is the PGIM hit list, which sorts alarms by activation frequency. Many alarm management projects have shown that a small number of alarms often make a highly disproportionate contribution to the overall alarm rate.

Typical nuisance alarms are:

- Chattering alarms, caused by badly adjusted equipment, faulty sensors or process noise
- Alarms that require no operator action, and should therefore be reconfigured as events

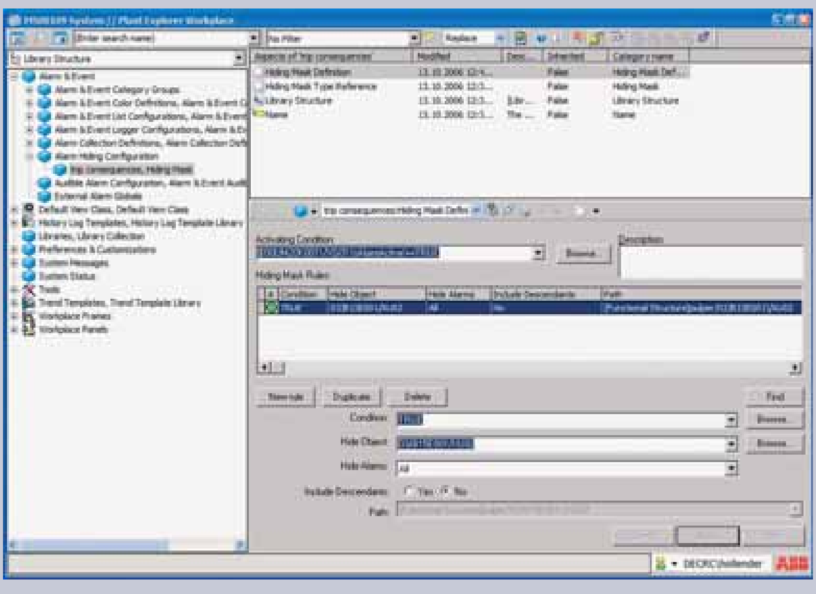
### Alarm rationalization

This is the process of reviewing alarms in the light of the plant's alarm philosophy. It includes the determination (and documentation) of each alarm's rationale and design requirements. The basis for the alarm setting, the consequence of deviation, and corrective action that can be taken by the operator may also be included, along with each alarm's priority status. Priority is often based on the consequences of the alarm or on its allowable response time.

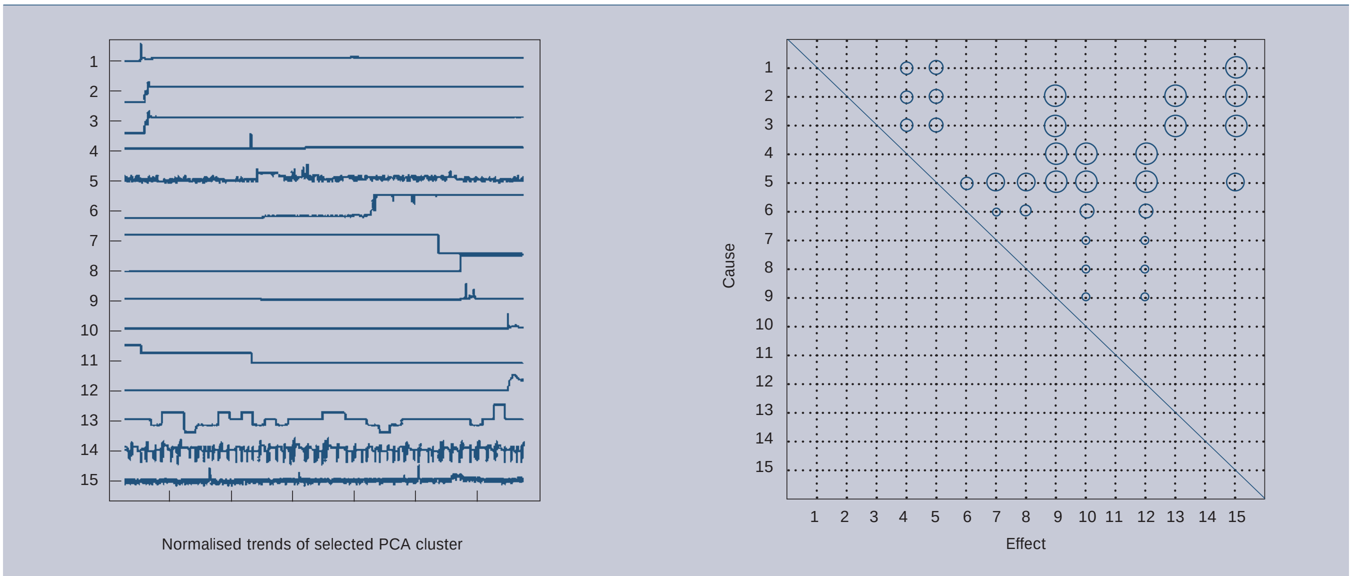
### Continuous improvement

As the plant changes over time, it is important to establish alarm manage-

2 System 800xA hiding mask



3 Mapping causal relations between process variables. The process variable 15 has a strong causal relation with process variables 1, 2 and 3. This can be used as a proposal for a process engineer to specify an alarm hiding rule.




ment as a routine part of the plant's procedures. (In the US, alarm management is often seen in the context of "six sigma" programs that target process variations that lead to subsequent breakdowns or failure of the process).

Nuisance alarms are alarms that serve no justifiable purpose, ie they are of no value to the operator. Such alarms exist in many plants and their removal can reduce the alarm rate significantly with very little effort.

### Hiding consequential alarms

Accidents like the one in Milford Haven show that operators can be overwhelmed by floods of alarms, especially in extreme situations. This is because a single root cause can have many different consequences, each of which triggers additional alarms. Basic alarm management, as described here, is not particularly helpful in such situations. In order to achieve EEMUA's target of no more than 10 alarms during the first 10 minutes of a process upset, a more rigorous approach must be taken. ABB's 800xA control system offers an alarm-hiding feature. This allows certain alarms (depending on process state or other active alarms) to be hidden from the standard alarm lists, but easily accessed when required 2.

It is a demanding task to identify all the causal relations between alarms that are required for the configuration of alarm hiding rules. Some commercially available Alarm Management tools can compute correlation coefficients between alarms. This analysis can be used as a basis for the configuration of alarm hiding rules. It is very important to note that those tools use binary data only (alarm on/off) and not the full richness of the original process data. It is obvious that by using historical process data more precise information about causal relations can be found.

To better understand the potential of this approach several days of historical data from two different plants was analyzed with Process Disturbance Analysis methods [6]. Some interesting causal relations have been identified which are currently being accessed together with process experts from the plants and shown in 3.

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[2] Tanner, R., Gould J., Turner, R. and Atkinson T. (2005), Keeping the peace (and quiet). ISA InTech September 2005.
[3] Norwegian Petroleum Directorate YA-711: Principles for alarm system design, 2001 (http://www.ptil.no/regelverk/R2002/ALARM_SYSTEM_DESIGN_E.HTM)
[4] Namur NA102: Alarm Management. 2005
[5] Hollifield, E. Habibi, The Alarm Management Handbook. 2006
[6] Horch, A., Peak performance, ABB Review 1/2007 pp24–29
[7] ISA RP18.2 Management of Alarm Systems for the Process Industries (draft)

Footnotes
1) OPC: formerly OLE (Object Linking and Embedding) for Process Control
2) SQL: Structured Query Language

# Peak performance

## Root cause analysis of plant-wide disturbances

Alexander Horch, John W. Cox, Nunzio Bonavita

Disturbances and oscillations in production processes usually have a considerable effect on product quality, running costs and profitability because production and throughput may have to back away from their optimum settings to accommodate process variability.

An international research and development team has developed an innovative solution for plant-wide disturbance analysis. After extensive field testing and collection of requirements, a Plant-wide Disturbance Analysis module has been productized and applied successfully at Eastman Kingsport, TN.

In their drive towards efficiency, modern industrial process plants are making increased use of recycle streams and heat integration. This integration of mass and energy complicates process control because variations can propagate through the plant in complex ways. Often, a single source of variation manifests itself as a widely distributed disturbance. A propagated disturbance can affect key process variables such as feed, product and recycle flows, column temperature and product composition. Such a disturbance can upset just a single unit, for example a distillation column, it can be plant-wide, affecting a complete production process or even site-wide if utilities such as the steam supply are involved. When there are many disrupted or oscillating measurements, finding the root cause of the disturbance is akin to looking for a needle in a haystack. The motivation behind the product development presented here is the automatic detection of plant-wide disturbances and determination of likely root causes. This allows disturbances to be removed or dealt with by maintenance, new control schemes or simply controller re-tuning.

In recent years, universities have developed several innovative algorithms based on advanced signal processing, spectral and nonlinear time series analysis for use in industrial process diagnosis. To better apply such knowledge to the problem described here, ABB initiated a project in cooperation with the Imperial College / UCL Centre for Process Systems Engineering (CPSE).

After preliminary field-tests, a large-scale pilot application of the methodology, using a first prototype implementation, was evaluated by ABB. The plant-wide disturbance technology was applied to measurement data from a Norwegian oil platform. The analysis of disturbances was based on data from more than 2000 measurement tags and more than one month's worth of data at high resolution.

In recent years, universities have developed several innovative algorithms based on advanced signal processing, spectral and nonlinear time series analysis for use in industrial process diagnosis.

Extensive analysis and discussion revealed significant disturbances that had also been identified by parallel plant investigations by process and process control experts from ABB and the customer. These encouraging results indicated that the intelligent analysis of process data can, to a great extent, help and support the work of problem identification, localization and diagnosis.

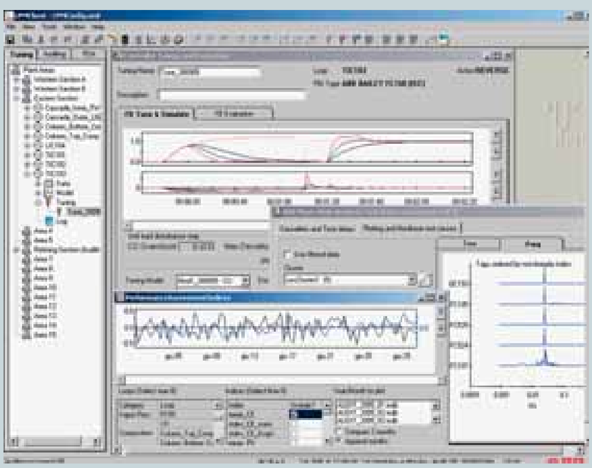
The final step in the product development process was the integration into ABB's product portfolio. Due to the nature of the methodology in supporting process performance analysis, it was chosen to productize the Plant-wide Disturbance Analysis (PDA) functionality as a new module in ABB's control loop optimization software Optimize^IT Loop Performance Manager (LPM). The release containing the PDA module is now available from ABB.

Following a brief overview of the methodology, this article will present two successful and surprisingly accurate findings from an end-customer evaluation of the tool. Eastman Chemical Company, Kingsport, TN (title picture), has been testing the integrated tool with encouraging results.

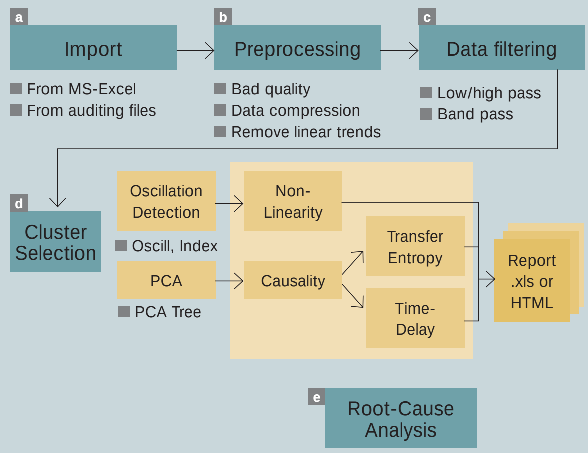
### Optimize^IT – Loop Performance Manager

Loop Performance Manager (LPM) is a control loop maintenance tool for control engineers, instrument technicians and maintenance personnel. It has been designed to provide a bridge between the technologies developed in academia, and the existing, relevant needs in the industrial world [4]. Its mission is to ensure that control loops, and – consequently – the whole production process, operates at peak performance.

1 LPM screen shot. A single environment for disturbance analysis, root cause detection, control loop monitoring and tuning



2 Typical work flow of PDA analysis within the Loop Performance Manager tool a to e are the five steps of this workflow



## Operational profitability

The package has been structured in a modular way, currently consisting of three software applications:
- A control loop-tuning component used to improve control loop performance
- A control loop-auditing component used to monitor loop performance
- A Plant-wide Disturbance Analysis (PDA) component. This software simultaneously analyzes multiple loops detecting common behavior and identifying likely root causes.

1 shows a typical screen shot of the LPM tool.

### Plant-wide disturbance analysis

A good survey of current research can be found in [6]. 2 shows the overall procedure of PDA within the LPM tool [7].

#### Data import

Data can be read offline from either Excel files or from data collected in the tool while performing control loop monitoring 2a.

#### Data pre-processing and filtering

Standard and simple functionality for data-pre-processing is very useful when different aspects of data, eg different frequency ranges are to be investigated. Also, problematic data, such as bad data, outliers or linear trends are filtered out automatically.

The simple representation of superimposed data in the form of a high-density plot, is already a very useful process for engineers. Such presentation modes are not usually available in historians or on operator screens 2b 2c.

#### Problem cluster selection

The first main step in the analysis is the detection of clusters of time trends that display similar periodically oscillating patterns. The oscillation detection is achieved with signal processing methods. In this context the signals are the time trends of the measurements. Oscillation detection has traditionally looked for zero crossings of the mean-centered signal. One weakness of this approach is that noise causes additional zero crossings, diminishing the value of the result. The key breakthrough applied here involves detecting oscillations using zero crossings of the signal's autocovariance function [1]. This provides a significant improvement over previous methods that used time trends directly 2d.

There is no restriction on the number of tags that can be handled. Past investigations used several hundred tags. These could be readily analyzed thanks to the efficient implementation of the underlying algorithms.

High-density plots as shown in 3 show time trends. An alternative way of viewing such information is by spectral analysis. This method highlights periodic features better than time trends. Frequency spectra have several advantages when it comes to the detection of distributed disturbances. However, it is the combined use of time and frequency approaches that is a strength of the described tool. The method employed to select clusters is based on spectral principal component analysis [2].

A powerful way of presenting the spectral clusters is by means of a hierarchical tree, as described in [9]. Spectral clustering also works very reliably for time trends with non-periodic features, as long as their spectra are similar. Other, very intuitive ways of representing clusters are also included in the tool.

#### Finding the likely root cause for disturbance clusters

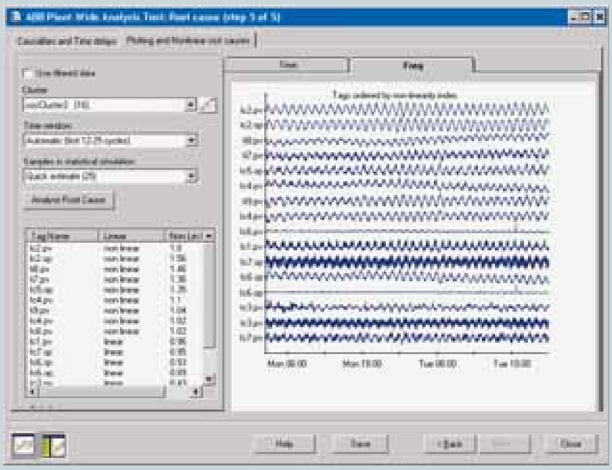
It is well known, eg [8], that a very common cause of disturbance in chemical processes is a faulty control valve with non-linear characteristics such as dead band or excessive static friction (known as stiction). The limit cycles arising from sticking control valves in a feedback control loop can propagate widely. For this reason, the tool was initially focused on the diagnosis of non-linear root causes. The methods developed for the diagnosis of sticking control valves can also be applied in locating faults originating in process nonlinearities such as periodic foaming in a distillation column or slugging flows in pipelines 2e.

### Nonlinear trends

A *nonlinear time trend* [3] is a signal that cannot be described as the output of a linear system driven by white noise. It is characterized by phase coherence and, if it is oscillatory, by the presence of harmonics. An example of a very non-linear signal is one with a square wave pattern. A process plant typically acts as a low pass filter, which means that a measurement close to a non-linear source has more non-linearity than a measurement far away from the source. The nonlinear square pattern is smoothed as it propagates through the plant. This behavior is utilized to identify candidate areas for root causes.

One way to detect non-linearity is by visual inspection of the time trends and the spectra. However, this is a manual procedure that is unreliable, intricate and prone to error. The novel concept in the current approach is a nonlinearity assessment that is strongest at the source of the nonlinearity. In this way, the root cause oscillation can be distinguished from propagated secondary oscillations. The assessment index is large for periodic but non-sinusoidal oscillating time trends (that are typical of the output of a control loop with a limit cycle caused by nonlinearity).

3 Oscillatory data from a cluster with 68 minute oscillations. Data is sorted by nonlinearity, correctly indicating LC2 as the root cause



The basis for the non-linearity assessment is a comparison of the predictability of each time trend and a set of constructed time trends that have the same power spectrum but random phases. A non-linear time trend will have a high predictability compared to the constructed time trends, whereas this difference will be small for a linear time trend [3].

**The nonlinear square pattern is smoothed as it propagates through the plant. This behavior is utilized to identify candidate areas for root causes.**

The power of the described methodology is underlined by the examples discussed below. A clear direction of operation and/or maintenance intervention can easily enable significant reductions in the time lost pursuing the wrong root causes. Furthermore, when applied to large-scale problems, the methodology enables the identification of problems that might never be identified manually since the root-cause may be located very far from its effect.

A data-driven, computer-aided methodology as shown here is a valuable support tool. It will not be able to replace human know-how but it can greatly reduce the effort in finding and mapping out the extent of plant-wide problems and locating their causes.

Two additional approaches to root-cause analysis are the use of transfer entropy and time-delay estimation methods [5].

### Transfer entropy

This statistical method evaluates the predictability of a variable from another variable based on probability density functions (PDF). The causality measure used to quantify the extent of the influence of a variable $X$ on another variable $Y$ is derived from transfer entropy $T(X|Y)$. The latter is itself derived from entropy which is a measure of uncertainty of a random variable and sums a weighed logarithm of the PDF. Transfer entropy is calculated from the joint PDF of two variables. This provides a measure for the dependencies between those variables. The causality measure $t(X,Y)$ is derived by comparing the influence of $X$ on $Y$ with the influence of $Y$ on $X$:

$$t(X,Y) = T(X|Y) - T(Y|X)$$

Thus, large values of $t(X,Y)$ indicate a strong causality from $X$ to $Y$.

### Time delay analysis

The second method implemented in the PDA module for causality analysis is based on the Cross-Correlation Function (CCF). This function determines causal relationships between measurements from the presence of time delay between them. The underlying principle of the method is that when the disturbance propagates through the plant, the disturbance can often be observed at a number of process variables with a time lag. Knowledge of the exact time lag provides clues towards the root cause because it can be argued that the variable closer to the root cause will show the disturbance earlier than a variable further away. The CCF measures the similarity between signals at different time instances and can therefore be used to evaluate time lags between signals.

**Key features of plant-wide disturbance analysis**

- Automatic detection of the presence of one or more periodic oscillations
- Detection of non-periodic disturbances and plant upsets
- Determination of the locations of the various oscillations / disturbances in the plant and their most likely root causes

**OptimizeIT Loop Performance Manager**

Combining bottom-up monitoring (control loop auditing) and top-down disturbance analysis (PDA) with world-class controller tuning functionality offers the most comprehensive tool for process control staff on the market.

**Industrial examples**

PDA (Plant-wide Disturbance Analysis) directed the process experts straight to the root-cause of plant-wide problems. These root causes were neither evident from looking at data nor from using process knowledge.

The CCF of two signals has a maximum value at a time value that is equal to the dead time.

The difference between these two methods for causality analysis is that the causality matrix based on transfer entropy is more sensitive. It can find a causal relationship even in situations with no measurable time delay, because it detects other effects such as smoothing of the time trend that occur as a disturbance propagates from its source.

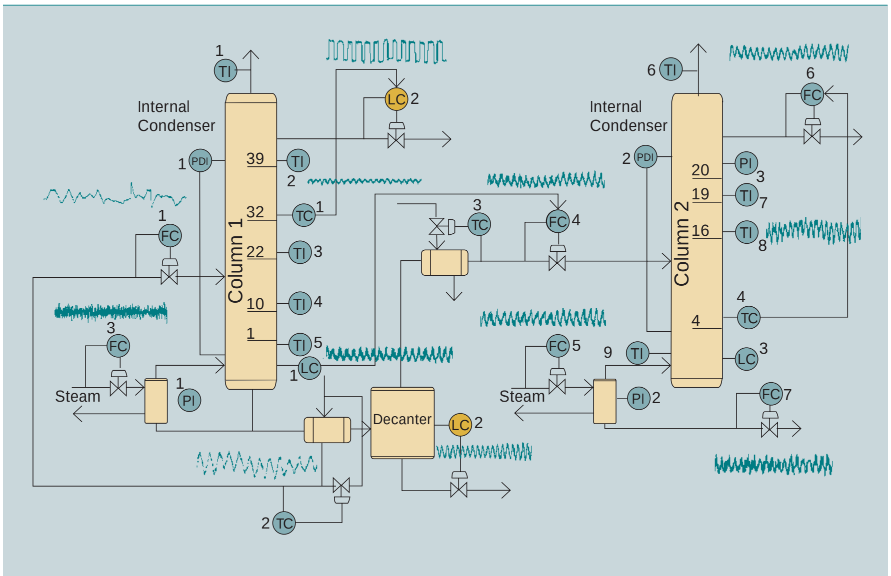
### A first industrial example

In the following, the process section of 4 is considered. This shows a section in a chemical plant consisting of two distillation columns. As can be seen, most measurements cycle with a period of 68 minutes (see also 3). Process experts suggested several theories explaining this sustained oscillation. Hence several root causes were suggested.

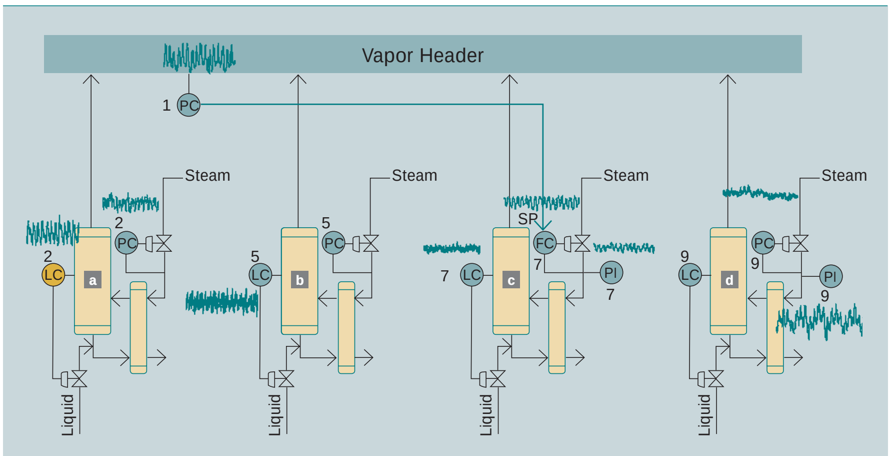
Applying PDA root cause analysis for the cluster related to 68 minutes cycle time suggested that a nonlinear problem around level control loop LC2 was causing the oscillations in all other tags in that specific cluster. This hypothesis was, in fact, experimentally verified: The control in LC2 was retuned 4–5 times as aggressively as its normal tuning. As a consequence, LC2 cycled at a much higher frequency and the downstream cycles in all the other variables no longer occurred. This gave the experts confidence that the root cause was within the LC2 loop and most likely a problem in the final control element. This hypothesis was also confirmed using LPM auditing analysis on the LC2 control loop data.

**Plant-wide disturbance analysis has moved from being a subject of advanced academic research into a successful industrial application in the form of a released product.**

4 Process schematic for Example 1




5 Oscillatory data distributed over a vaporizer system. The identified root cause is marked red.
a – d are vapor columns




A likely explanation for the plant-wide upset is that the oscillation propagates through the plant section as the decanter is filled with liquid. As a result, there is more or less flow through the LC2 valve and this affects the LC1 level measurement. LC1 in turn adjusts the feed FC4 (via the master-slave feedback) to column 2. The resulting cycles in FC4 affect several column 2 variables, including the distillate flow FC6.

There was also a secondary cycle in the data set. This oscillation was somewhat faster and the cluster involved another five measurements. Root cause analysis gave early indication of stiction behavior in FC2 – this is a correct result.

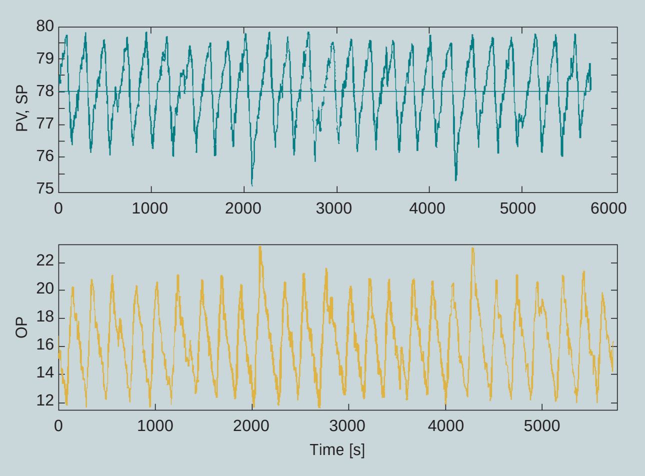
On the basis of these results, maintenance staff can improve the complete plant section peformance by attending to the two indicated valve-related problems in LC2 and FC2.

### Second industrial example

This example describes the disturbances found in a vaporizer system 5.

It can be seen that the pressure in the vapor header is oscillating at a period of 220 seconds. This frequency can clearly be found in all four vaporizers (5a 5b 5c and 5d) that are used for steam and pressure generation. Vaporizer 5c is used for pressure control in

6 Level control loop LC2 data in Vaporizer A. a setpoint and process variable (0-100 percent), b manipulated variable (valve opening) (0-100 percent). The data shows a sticking behavior.




Factbox LPM Auditing output

```
- LC2: Overall loop assessment:
------------------------
The control loop performance is not acceptable.
- LC2: Detailed information:
------------------------
The control loop is oscillating.
- The control loop is oscillating.
- The control valve exhibits stiction that results in
  loop oscillations. Put controller in manual to
  verify.
The oscillation accounts for a significant part of
the overall variation. Removing the oscillation will
have lead to great improvement.
The oscillation amplitude is quite regular. This is
untypical for a pure (linear) tuning problem.
- The final control element introduces variability to
  the output.
The control valve suffers from increased static
friction (stiction). A malfunctioning valve increases
loop variability. Put loop in manual or maintain
valve.
```

the header. A natural first guess by plant staff for a root cause was to investigate the vaporizer 5c.

**When applied to large-scale problems, the methodology enables the identification of problems that might never be identified manually.**

However, when applying PDA to this problem, a cluster including all related tags was easily identified. Using nonlinearity analysis, the level control loop (LC2) in vaporizer 5a was identified 6.

Experiments performed by process control experts actually verified that this was the – non-intuitive – root cause. In order to exemplify how LPM can be used for further confirmation, LPM Auditing was applied to this loop. It generated the following diagnosis which was found true in the plant Factbox.

## Conclusions

Plant-wide disturbance analysis has moved from being a subject of advanced academic research into a successful industrial application in the form of a released product. The industrial cases show that innovative, modern technology offers great help to process experts in their root-cause analysis of important plant problems. These root causes are not always evident to plant personnel and advanced tool support can greatly reduce time spent on localizing these causes.

The unique combination of top-down and bottom-up approaches which combine the most important tools for process control engineers makes the ABB tool very powerful. Furthermore, encouraging results have been achieved by applying the PDA methodology to new fields of application, eg, advanced alarm management and supervision and diagnosis of electrical networks.

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# Design methods

## Putting the human in focus

Charlotte Skourup, John Pretlove

How many people would dare board a plane without a pilot on board even though technology has advanced to a point where “flying” a plane from the ground is possible. Can technology be trusted enough to also run nuclear power plants or complex industrial processes without the presence of operators? Of course people make mistakes and often accidents such as nuclear meltdowns or airplane crashes are attributed to human error. However, in many cases a lack of relevant information for handling a critical situation has been at fault.

Rather than eliminate humans from the process, the trend nowadays is to fully utilize their capacities and strengths by integrating them more into the overall design. This means designers must harmonize two very different complex models – that of a technical process control system with one representing human behavior – to produce a well-functioning automation system that cannot afford to fail in critical and unpredictable situations. This article gives an overview of how this is done.

In general human nature is uncomfortable with the idea of giving away overall responsibility for a complex process – a pilotless plane is evidence of that. Another example to illustrate this comes from the oil and gas industry where the trend is to move the operation of offshore installations to onshore centers to reduce personnel risks and operational costs. Some teams, however, need to remain offshore not only for safety reasons but also to perform inspection and maintenance tasks. Understandably, there is considerable apprehension towards moving control and responsibility hundreds of miles away from the process itself. Because the operator is such an important element in any automation loop – especially when critical and unpredictable events occur – new systems need to be designed with an extended focus on the human user. A poorly designed system can have dreadful consequences of which the Three Mile Island nuclear accident is a good example Factbox.

The accident was a catalyst that brought about a new way of thinking in terms of system design. While many technical issues needed to be re-examined, so too did the role of the human operator in certain industrial processes. Following the accident investigation, sweeping changes were made to emergency response management, operator training and, more importantly, human factors engineering for plant operations. Many of these changes later filtered through to other industries.

Many institutes have researched the role of the human in industrial processes. The Institute for Energy Technology (IFE) in Norway, for example, has focused[1)] its research on: human cognitive processes; design and prototyping; and task allocation. Similar research in other safety critical industries, such as oil and gas have been following the same trend. Other process industries with fewer safety requirements have been relatively slow at introducing new methods, paradigms and thinking related to safety concerns and the human user. This is, however, beginning to change as new design approaches supporting cognitive elements are gradually finding their way into the industrial marketplace.

### Knowing the human mind

Models of human mental processes and behavior, and user-centered design increase the focus on the operator as an integral part of an advanced automation system. Many such models exist and each represents some aspect of the cognitive processes of the human mind. Two of these are discussed in the following paragraphs.

## Models of human mental processes and behavior, and user-centered design increase the focus on the operator as an integral part of an advanced automation system.

*Rasmussen* [1] has developed a model to help designers combine information requirements for a system with aspects of human cognition. Also known as the SRK (Skills-Rules-Knowledge) model, it describes three levels of human behavior: skill-based, rule-based and knowledge-based 1. Skill-based and rule-based behavior patterns represent situations and tasks that are familiar to an operator. To be more specific, the skill-based level requires almost no conscious human control or cognitive effort to perform an action based on perceived inputs. Human performance at this level is automated and consists of highly integrated patterns of behavior acquired through training. The rule-based level occurs when a situation or an event is familiar and the operator uses a selection of acquired rules and procedures to formulate a course of action. Operators base their performance on this type of behavior when they follow specific maintenance procedures, for example. The knowledge-based level of behavior is the most demanding cognitive process and it takes place when the human experiences an entirely unknown and unexpected event or situation.

Unlike many other models of human cognitive processes, Rasmussen's model is based on industrial process operators and how they manage information and perform tasks. This model is therefore highly relevant for complex industrial automation systems.
In practice, Rasmussen's model can be used to decide at which level of behavior the operator performs specific

**Factbox** Three Mile Island nuclear accident – an overview

Three Mile Island nuclear generating station sits on a 3.29 sq. km island in the Susquehanna River in Dauphin County, Pennsylvania. In 1979 a sequence of events led to the partial meltdown of the nuclear reactor. Initially a failure in the cooling system caused a relief valve to stick in the open position. Signals to the operator failed to indicate that the valve was open. As a result cooling water continued to pour out of the reactor causing it to overheat. There was no indication of the level of coolant in the reactor. Instead the operators judged this based on the coolant level in the pressurizer, and since this was high, they assumed the core was properly covered.

Even as alarms rang and warning lights flashed in the control room, operators failed to realize the seriousness of the situation. In fact a decision to reduce the flow of coolant into the reactor only served to exacerbate the situation. In the investigation that followed, it was discovered that the operators did not have all the information necessary to understand the real situation. Because of the lack of information, the operators' "picture" – or mental model – of the situation was wrong and all actions taken were based on this incorrect model. Even when the predicted outcomes of specific actions did not match the mental model, operators disbelieved alarms rather than question their own understanding of the situation.
For more detailed information, please refer to www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html (Referenced in November 2006).

tasks and what information should be available at this level. It can also allocate tasks between the human and the control system.

### Situational awareness – prerequisites for human decision making

*Endsley's [2] situation awareness model* describes how people who deal with complex and dynamic systems – such as an industrial process – actively look for and interpret specific information, and how decisions are made based on this information. Endsley's model comprises three levels 2:

- Perception of elements in the environment within a volume of time and space.
- Comprehension of the meaning of these elements.
- Projection of the elements' status into the near future.

The first level describes how the human perceives bits of information in an environment that either deviates from the original situation or represents a state that contributes to the "picture" of the current situation. At the second level, the person acquires a deeper understanding of the current situation while still actively searching for additional and complementary information. Finally, the human operator uses his mental model of the industrial process to simulate potential actions based on perceived information as well as the present interpretation and understanding of specific information. When a solution has been found which solves the problem the decision regarding what actions are required naturally takes place.

The challenge of good system design is to fully utilize the strengths of both man and his "machine" (the control system) to achieve what neither can alone.

Endsley's model helps designers understand how automation and decision support systems collaborate to direct the operator's attention to specific information essential to comprehend any given situation. In practice, it can be easily applied and is especially effective where there are long periods of normal or low activity that are suddenly interrupted by the occurrence of a critical event requiring the operator's full attention. It does not, however, say anything about the individual's mental "picture" or any decision the human operator will take.

### Designing for improved human-machine collaboration

The challenge of good system design is to fully utilize the strengths of both man and his "machine" (the control system) to achieve what neither can alone. Where technology-centered design focuses entirely on the technology, user-centered design aims at developing technology to support the specific user and his tasks in context.

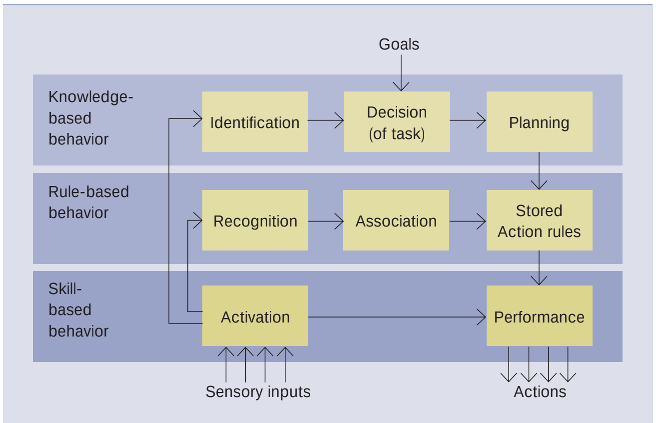
The job of integrating the human operator into a well-functioning automation system belongs to the system designers. Even though the system design process – which includes a number of phases, analysis and methods – varies between different industries, the common denominator for all designers is that they must collect relevant information on the *human in the loop* to design an effective human machine interaction. Such a system acts as a communication channel between the operator and the control system.

### Requirement specification

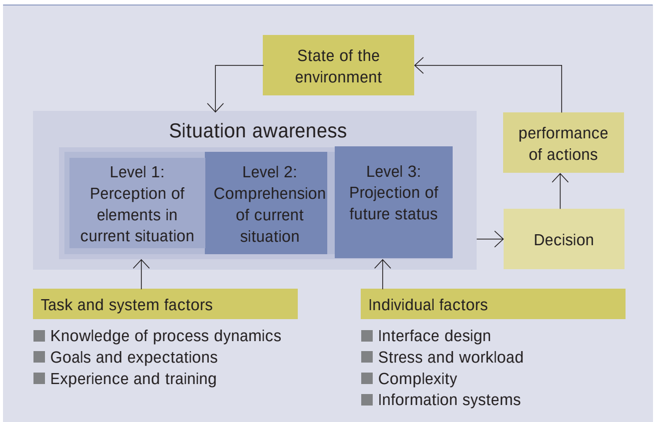
Almost all designers perform a requirement analysis to translate overall system goals and objectives into specific system specifications. Few however focus on the human user as part of the overall system. A complete set of design specifications should consider the industrial process itself, the users, the tasks, the environment and the operational requirements. Knowledge about the operator and how he performs his tasks ought to drive the design of the automation system.

A user analysis identifies the different users of the automation system. It further groups and characterizes these users based on bibliographic information, competence, experiences and preferences. This type of analysis helps the designer to get to know the users and to understand how they perform their tasks. Additionally, environmental requirements relate to ex-

1 Rasmussen model of human behavior – also known as the SRK model – helps designers combine information requirements for a system and aspects of human cognition




2 Endsleys situation awareness model describes how people in complex and dynamic systems look for and interpret information, and how decisions are made from this information



ternal factors such as the layout of work places, lighting conditions and the surrounding environment (ie, explosion risks, dust, humidity, noise, etc.).

### Functional analysis and task allocation

Functional analysis identifies the functions of the entire automation system including both the human and the control system. The main objective of a functional analysis is to allocate labor – also referred to as task allocation – between the human and the control system. Use cases and scenarios are examples of techniques needed to gather functional requirements.

It is recognized now more than ever that the human operator is an irreplaceable part of the automation loop, especially when critical and unpredictable events occur.

In many situations, task allocation can be pretty straightforward: nothing matches a computer, for example, when it comes to handling large amounts of data, performing repetitive tasks and following procedures. In addition visualizing and ergonomically presenting complex information in terms of overviews and drill down objects is easier. The human, on the other hand, is good at reasoning, judging, solving problems and making decisions. However, the real world is not black and white and many tasks demand close collaboration between the computer system and the human operator in order to solve a task optimally. As well as task allocation, the degree of automation is a highly relevant topic. The complexity and degree of automation varies within different industries and sometimes even within a specific process. Also, the way human operators react to problems and situations is dependent on their experiences and skills. However, a conscious decision regarding the level of automation and when the human operator should interact with or override it is essential. This important guideline makes the operator's workload "visible" to the designer.

### Task analysis

The main aim of a task analysis is to understand the tasks, goals and expectations the user will demand of a new system. It is therefore critical to clarify which tasks an operator should perform to get the job done. The order in which the tasks are carried out to fulfill the goal and the tasks themselves may differ between operators so long as safety is not compromised. A basic task analysis, for example, identifies a number of goals and the related tasks needed to achieve each goal.

A number of variations of task analysis methods exist. Two such variations are known as *Hierarchical Task Analysis and Cognitive Task Analysis*. A Hierarchical Task Analysis simply divides a job into tasks based on a hierarchy whereas a Cognitive Task Analysis focuses on the cognitive processes needed to perform a task. For example, a field inspection is a rather simple task to define. On the other hand, an unexpected situation novel to the operator demands a higher level of definition. According to Rasmussen's model of human behavior, this task takes place at the knowledge-based level of behavior, which means it may involve tasks such as problem solving and decision making. With this knowledge designers can then determine (a) what information the operator should see and how it is presented, and (b) the decision support and task allocation between the control system and the human operator.

### Conclusions

The trend within almost all industries is towards safer systems (despite increasing complexity) and a higher level of automation. The design process in the past was more technology-centered, but now there is a growing focus and understanding of the importance of the *human in the loop*. It is recognized now more than ever that the human operator is an irreplaceable part of the automation loop, especially when critical and unpredictable events occur. People are however different and unpredictable and respond in slightly different ways to critical situations.

A complete set of design specifications should consider the industrial process itself, the users, the tasks, the environment and the operational requirements.

A number of methods support an extended understanding of the *human in the loop* and help to define and characterize the typical operator or groups of operators. To ensure a well-designed and safe automation system, the system designer will, now and in the future, need to combine the outcome of these various models and methods.

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Footnote

1) Initially for nuclear power plants.

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Further reading

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# Case Study

## Prototyping at Statoil Tjeldbergodden

Trond Tysseland, Torgeir Enkerud, Kristoffer Husøy

A number of models and methods support an extended understanding of the *human in the loop* by involving actual users. This was successfully applied through low-fi prototyping and operator involvement in a project to upgrade the control room at Statoil Tjeldbergodden.

Statoil Tjeldbergodden 1 is an industrial complex situated on the mid-western Norwegian coastline. It comprises four areas: a methanol plant, a gas receiving station, an air separation plant and a gas liquefaction facility [1]. As part of a major modification of the plant, it was decided to upgrade the existing Infi90 control system human machine interface (HMI) to ABB's System 800xA.

It was determined that the new system should handle 20,000 tags and would consist of approximately 240 process graphics.

The models and methods used in this case study have been introduced in [2] and a brief overview is given in the Factbox 1. This case study particularly focuses on how low-fi prototyping Factbox 2 was applied to the control room upgrade project. By using this simple and effective technique, several iterations of the design were completed with minimum effort.

### Information navigation

The problem faced by knowledge workers and control room operators in many industries is how to find the right information quickly and efficiently. The control system operator interface often consists of anywhere between 20 and a few thousand process graphics, and the operators must be able to quickly identify and navigate to the right one.

The system used at Statoil Tjeldbergodden prior to the upgrade meant operators had to navigate through links in the process graphics 2. These links were scattered everywhere, often following the process flow. To find the quickest route to the desired graphic meant operators had to be very familiar with the plant layout. Clearly a new HMI was necessary.

### Thumbnails for browsing

The first design proposal was inspired by navigation in Microsoft PowerPoint, Windows Explorer and some photo editors where the idea of thumbnails is employed. Basically, a thumbnail is a small visual copy of an object and acts as a direct link to the object. Thumbnail navigation is an intuitive way of navigating because the user can recognize the visual content of the object that is sought, especially if there are many of them, without having to remember its name. When applied to process graphics, the idea was to use simplified images of these graphics as thumbnails in a panel along one side of the screen display 3. Overlaying the thumbnails with dynamic information – for example showing the number of active alarms with highest priority or other aggregated status indicators – was considered to add extra value.

The concept demonstrator was developed in a graphic editor and inserted into Microsoft PowerPoint presentation slides. Several images were created that contained different process graphics. The corresponding thumbnails showed which process graphic was selected as well as some alarm information. This allowed the designers to demonstrate the concept almost like a working prototype, where clicking on a thumbnail would move to the next slide or "sublevel" showing a new process graphic and its corresponding thumbnail.

The user tests were conducted in an informal manner through a workshop attended by operators, site management, ABB project team and developers. The users liked the concept of a dedicated navigation area, but there were some issues with the thumbnails:

- There was not a sufficient number of links at a time.
- The "visual recognition" effect was not very important because many process graphics look similar.
- The level of detail in the thumbnails was judged to be too high, thus cluttering the operator interface.

### Tabbed browsing

With this feedback in mind, the team started a new design phase. With inspiration from the Opera web browser, Microsoft Excel and Microsoft Visual Studio 2005, a concept of using tabs

**Factbox 1** Models and methods applied in industrial automation system design

Many models of humans with respect to how they perceive and process information exist. Each of these represents some aspects of the cognitive process of the human mind, thus helping designers to better understand the human operator in his respective role.

**Rasmussen's model of human behavior** – also known as the SRK model – helps designers combine information requirements for a system with aspects of human cognition. It is used to decide (a) at which level of human behavior (skill-based, rule based or knowledge-based) the operator performs specific tasks and (b) what information should be available and presented to the operator. This model can also be used to give an overview of specific tasks allocated between the human and the control system.

**Endsley's situation awareness model** describes how humans look for and interpret information in complex and dynamic systems, and how decisions are made based on this information.

The system design process includes a number of methods related to collecting relevant information on the *human in the loop* that impacts the design of the human machine interface (HMI):

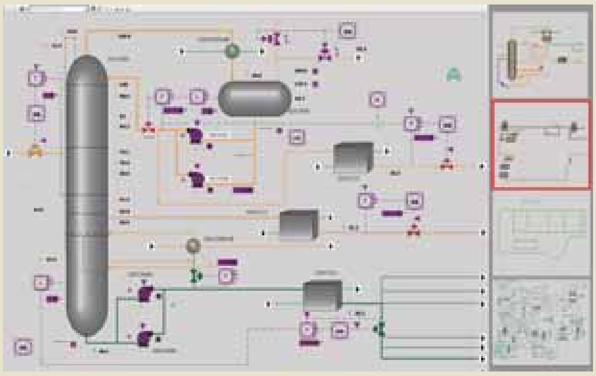
- A **Requirement Specification** translates overall goals and objectives of the system into specific system specifications.
- A **Task Analysis**, of which there are two types: **Hierarchical and Cognitive**, aims to understand the task, goal and expectations which the user will demand of a new system.
- A **Functional Analysis** – also referred to as task allocation – divides the labor between the human and the control system.

To ensure a well-designed and safe automation system, the system designer needs to combine the outcome of the above-mentioned various models and methods.

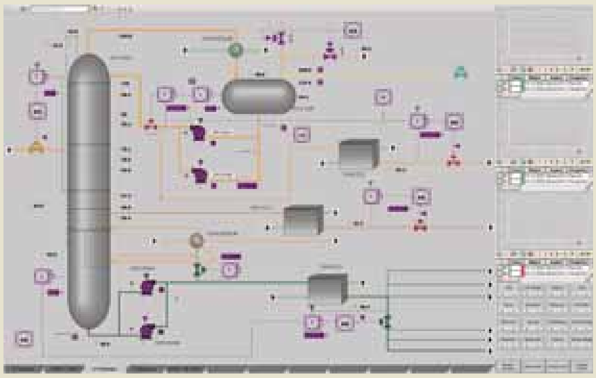
1 The Tjeldbergodden site

2 A screenshot of the old system with display links

3 Thumbnail navigation



4 Tab navigation



for process graphic navigation was developed. By building on the mental idea of flipping through paper documents in a pile, tabs would be employed to enable the user to quickly switch between several documents within an application. When used for process graphics, the idea is to position a bar of tabs at the bottom of the user's screen in combination with a navigation area on the right 4. The tabs show all process graphics in a process area, while the navigation area is used to navigate between the various areas.

The user tests were again implemented using image editing and Microsoft PowerPoint, and several interesting issues were revealed:

- The users have a mental model of a logical and structural hierarchy of process graphics in the plant. This hierarchy is based on the different functional areas of the plant, and the displays could be organized into three different types:
  - Process displays – showing a section of the process on an overview level
  - Detail displays – presenting more details about a part of the process shown in the process display
  - Matrix displays – showing the shutdown logic for a section of the process
- The users would like to navigate directly to detail and matrix displays from the navigation panel, not via the respective process areas.
- The users couldn't find a way of navigating directly from a detail display to the parenting process display without first having to think about which area they were in.

**The use of paper prototyping combined with knowledge and ideas from experienced users means final designs are usually established with a low level of effort.**

The final step in the paper prototyping process was to include the users' suggestions in finding a solution to these three problems. The first suggestion centered on direct access to the detailed tabs panel and matrix tabs panel for each of the process areas through links in the navigation area. The second suggestion was to include a context-sensitive "up"-button in the tabs panel for the detail displays that navigates directly to the parent of the current display.

### Conclusion

The use of paper prototyping provided several benefits for the project team. First of all, the concept was quickly developed, and because simple paper prototypes were used, the final design was established with a low level of effort. Experienced users are a great source of ideas and knowledge. Bringing them into the project at an early stage lead not only to a feeling of ownership but also to a feeling of having contributed to the final solution.

Factbox 2 Lo-fi prototyping

Low-fidelity (Lo-fi) prototyping is used to get user feedback as quickly and as efficiently as possible. Normal prototyping often involves some form of construction and/or programming, and developers must often wait until the main product is almost finished before testing can be carried out using potential users. Lo-fi prototyping, on the other hand, uses simple methods, such as sketching on paper, PowerPoint and image editors, etc, to create straightforward mock-ups that demonstrate the main functionality – all within a matter of hours. This method ensures that user feedback comes at the very beginning of the project rather than at the end, making major changes possible.

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# Projections of productivity

## An operator's dream: Ergonomics for the control room

Per Lundmark

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

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

This workplace builds on ABB's unique System 800xA software and continuing technical progress. It was developed in conjunction with two Scandinavian companies, and is now being released onto the market. The first installations are completed and several customers within the process industry are awaiting their deliveries and installations. The expectation is that a more effective, safe and profitable production will ensue 1.

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

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

An other comment is that the Extended Operator Workplace is effectively combining a large overview display with several regular monitors, all with full interaction.

"The most important thing is that our operators can see the entire plant in an overall picture, as well as viewing several other selectable images at the same time. When a fault arises they can see it and respond more quickly. It is also easier to remedy. This enables us to minimize the number of halts in production".

A number of different customers are awaiting delivery of this new presentation technology. Process industries, petrochemical industries and combined power and heating plants are amongst those who have seen the advantages of having an efficient workplace for their operators.

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

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

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

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

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

The development work followed a number of guidelines for a good control room workplace:

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

The most important thing in a new control room workplace is the option of displaying an overview. It is common in many control rooms in most industries to have large screens that do not offer any means of interaction and often only display images of trends that are not of particularly great use. The operator in such a room struggles with perhaps only two monitors, incomplete information, and ineffectively placed video monitors for the important camera monitoring.

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

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

The overview offered by System 800xA Extended Operator Workplace

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

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

Operators are offered optimal support by interactive display technology from ABB


owes its advantage to the flexibly configurable display of information on different screens and projectors. Overview pictures can, for example, be displayed on the entire large-screen, while the monitors show details, diagrams or other information. Or conversely, a single image, a diagram for example, can be spread across three monitors as one total picture while the large-screen shows trends in smaller windows. All images are opened correctly and automatically by the software in 800xA Operations, in separate windows and in a clear and readable format.

**It is common in many control rooms in most industries to have large screens that do not offer any means of interaction and often only display images of trends that are not of particularly great use.**

The large-screen can be used in different ways:
- As a single continuous image
- In order to display all images in the system as overlapping images
- In order to build up group pictures of multiple images
- For displays for visitors
- For "live video", instead of separate video monitors.

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

The improvements to the working environment include the ability to raise and lower the curved working surface and the desk. Similarly, the large-screen can be raised and lowered, as well as slightly bent in order to present a clear image from where the operators are sitting. By mounting the large screen directly at the rear of the desk instead of on a wall, as is usually the case, the overview is not disturbed by passers-by. An additional improvement to the working environment is the option of moving the computers entirely outside of the control room to deal with the prevalent issues of heat, noise, space, and security.

An example of how this can be done leverages new technology developed by the electronics company, Matrox Graphics. Matrox introduces a transmitter card on the workstation or server which replaces the standard graphics card and can be fiber-optically cabled to a remote graphics unit on the operator side. The remote graphics unit contains all the necessary I/O including: four monitor ports, six USB ports for peripherals such as keyboard and mouse, and audio connections for speakers. Matrox remote graphics units 2 work with all installations of System 800xA.

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

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

System 800xA Extended Operator Workplace has been shown at a number of trade fairs around the globe, where it has always met with a great deal of interest. Many visitors shared the assessment that "ABB's workplace is precisely what we want!"

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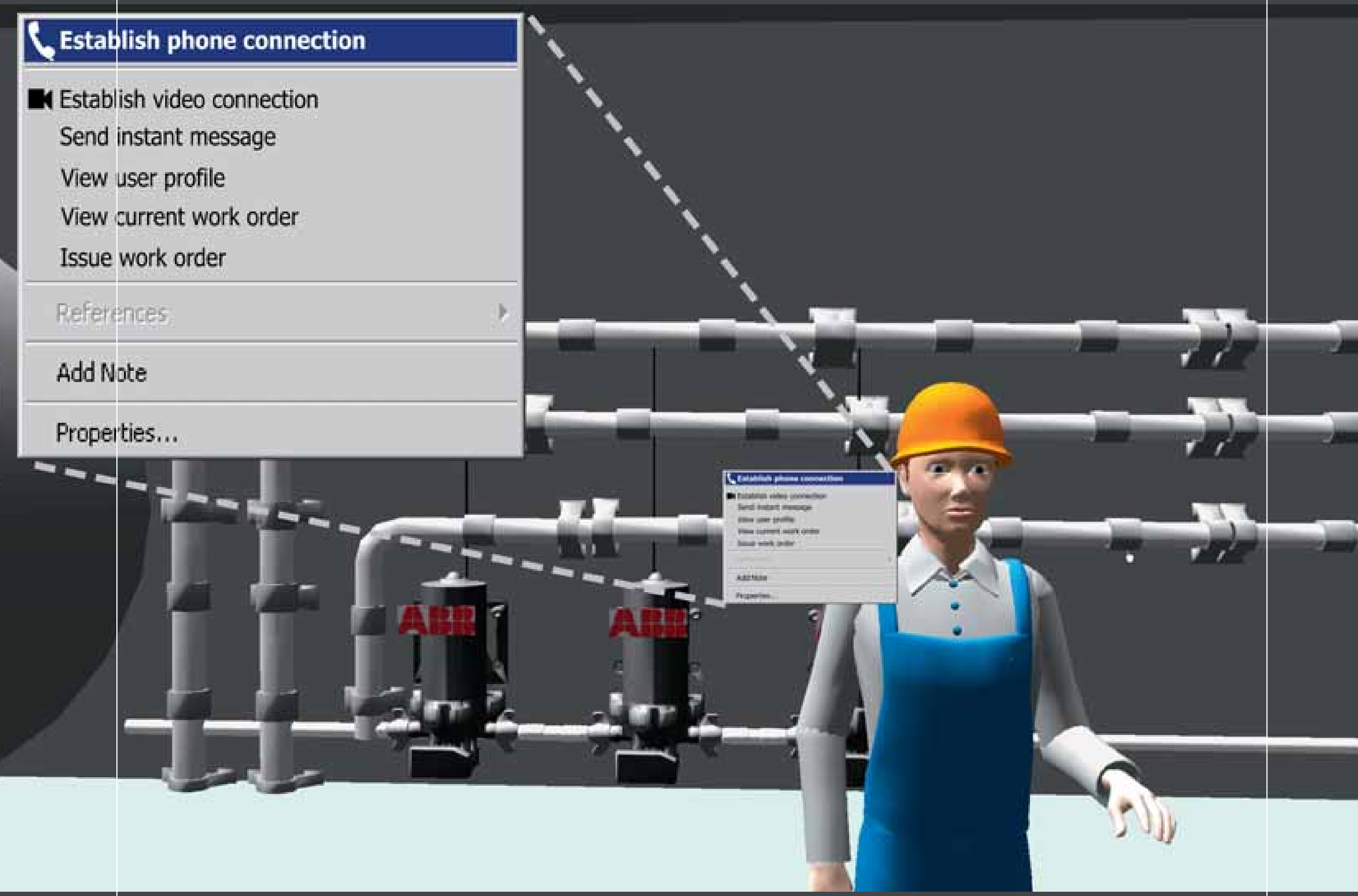
# Spatial awareness

## 3D representations improve situational awareness for control room operators

Kristoffer Husoy, Torgeir Enkerud




Progress in both computer power and control algorithms are permitting computers to handle increasingly complex tasks in process control. What then, is the future for control room personnel? The scenario of the computer having the control room to itself is unlikely in the foreseeable future – the human ability to think creatively, exercise judgement and improvise remains unrivalled. However, control room personnel are moving into positions requiring a broader overview. As a result, operators have less detailed knowledge of the plant. Staff effectiveness is increasingly depending on the method in which information is presented to them.

ABB is developing a three-dimensional representation for the oil and gas sector. The operator can see inside the plant and gain an overview of what is happening inside. The 3D view also aids communication with field personnel, as both see the plant in the same way, so reducing the risk of misunderstandings leading to incorrect actions.

Today's industrial processes are controlled by human operators, who in turn are supported by industrial control systems – a situation that is unlikely to change in the foreseeable future. In spite of rising levels of automation permitting reductions in manpower and hence operational expenses, the unique creative and problem-solving capabilities of humans will remain indispensable at the control desk for many years to come. This means that operators and automation systems must continue to monitor and control such processes in collaboration. A clear and efficient communication between the two parties remains a prerequisite for the optimal functioning of industrial processes.

This is the basis of an ABB research project in Norway, focused on the needs of oil and gas plants. In such installations, the control system needs to display information in a clear and intuitive manner to let the operator do what she does best: interpret information, solve problems and be creative. When the control system presents its information in a manner that is well suited for human interpretation, the operator can digest more information and grasp what is going on more quickly.

### Operators in control

The overall safety and operation of a plant relies on human operators being in control and playing a decisive and indispensable role in overall plant operations. Today, processes are mostly controlled from a central location – the control room. The operators in the control room are responsible for the day-to-day monitoring of the process. This involves making key decisions such as setting optimization levels for the process, scheduling maintenance and responding to critical alarm situations.

When the control room operators are located away from the plant, they will not be able to maintain detailed knowledge of physical locations and spatial relations of the plant.

But the operators in the control room do not run the plant by themselves. They rely on personnel in the field. These field operators are the hands and eyes on the plant floor. Their activities include operating, configuring and calibrating the equipment, as well as performing maintenance and service operations in conjunction with the dedicated maintenance and service teams. Furthermore, the process engineers, instrumentation engineers, remote experts and administrative personnel also play a role in the daily operation.

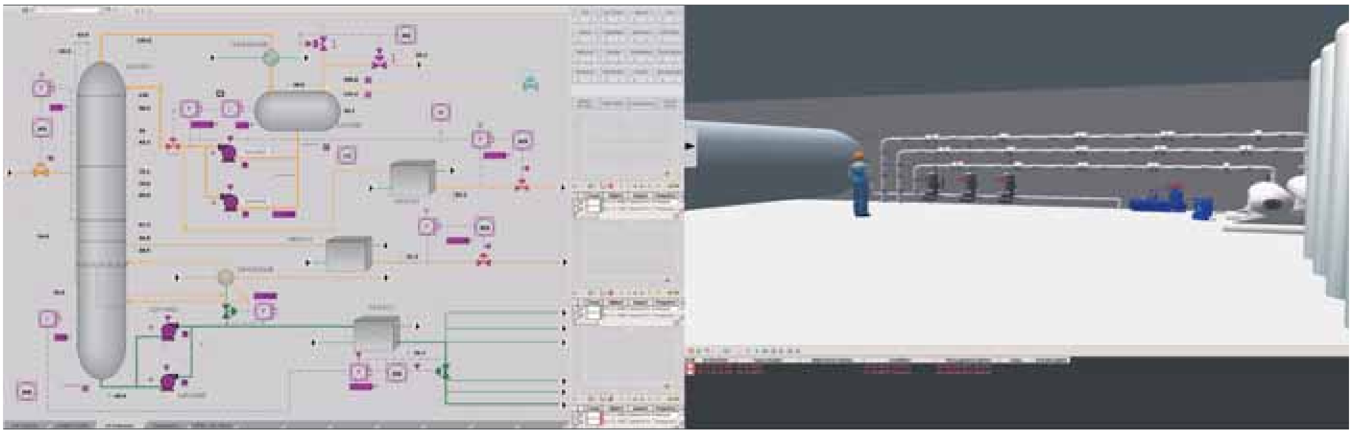
The overall performance of the plant is dependent on all systems and actors performing well together. This collaboration can take the form of co-located collaboration, or remote collaboration. In co-located collaboration the process control operators, field operators and managers come together to discuss problems and plan operations. Examples might be shut-downs, start-ups, maintenance schedules and optimization issues. In remote collaboration, the on-site personnel collaborate with remotely located personnel – either field operators or remote experts. For example, when maintenance is performed in the plant, the process control operators and field operators work together to ensure that the operation is as safe as possible. The process control operators make sure that the equipment is properly sealed off and aid the field operators in their maintenance task.

Both of these scenarios require close collaboration between individuals with different domains of expertise and often with different cultural, technical and social backgrounds.

### The future is coming

Looking ahead, several trends can be identified that will have an impact on the control room operator's situation and role. The principal among these is the centralization of control rooms, which has recently been pushed by the demands for higher profitability, cost reduction and safe and efficient operation. This trend – often referred to as "Integrated Operations", "eFields" or "Fields of the Future" in the oil industry – will have great impact on the way industrial plants are controlled in the future.

Tight integration of the traditional operator interface with the proposed 3D interface is crucial to enhance efficiency and support operator's situation awareness



When the control room operators are located away from the plant, they will not be able to maintain detailed knowledge of physical locations and spatial relations of the plant. This might lead to field operators becoming the only personnel with detailed location-specific knowledge, whereas control operators take over more administration and optimization related tasks. This trend will also probably lead to one control room operator controlling larger plant areas or even several different plants.

> The operator can navigate around the model, investigate details, get an overview and clearly see the physical and spatial relations.

Furthermore, there is a tendency for oil companies to want suppliers to be responsible for equipment and subsystems through service agreements to a larger extent than before. The suppliers – such as ABB – will not want to place personnel at all sites, but rather monitor and control equipment from a central location. This will require the suppliers to have access to relevant, live, on-line data from the plant, and efficient means to communicate and work together with onsite personnel.

Finally, there is a clear tendency for advances in instrumentation and measurement systems, computing power and network capacity to produce greater amounts of data. Not only will such data be transmitted more frequently, but there will be more sensors transmitting it to the control room. This will lead to even more data being fed into the control room, with increased risk of information overload.

### The human perspective

Interpreting these tendencies, the trend towards minimizing the number of operators remains, but it is neither realistic nor desirable to wholly automate such processes. So, for the foreseeable future, human operators will remain in control and will depend heavily on their ability to communicate with the automatic parts of the control system. When looking at this from the human perspective, a range of interesting implications for a control system supplier such as ABB becomes evident:

#### Support operator's situation awareness

The operator must understand the state of the plant at all times. This means the operator needs to get the right information, the appropriate amount of information and most importantly, the information needs to be displayed in a manner that the operator can assimilate and can react to.

#### Ensure optimal allocation of tasks between operator and system

There should be a conscious decision in selecting the tasks that should be handled by the operator and those that should be automated by the system. One perspective on this choice is that this decision should be based on an understanding of which of these can perform the job best. In this manner the performance of the system, including human and computer, can be optimized. This holds that the tasks allocated to the human operator match human abilities, and that the computer handles the tasks it is best suited for Factbox.

#### Support remote and co-located collaboration

As described above, there are many parties that contribute to successful plant operation, and it is important to support collaboration between them. This means the collaborators need access to the same information; they need to be able to share information and they need to get an understanding of each other's situation and context.

> The physical limitations of what a field operator can and cannot do, the physical relationships between different objects and the location of components are immediately and intuitively understood when viewing a 3D representation of the plant.

### 3D visualization to the rescue

A research project in ABB Oil & Gas Norway is currently investigating how a 3D interface of the plant and process can remedy the problems described above. The idea is to use 3D models of the plant and all equipment in the operator interface. The 3D models are assembled with correct dimensions compared to the real plant layout, and the 3D models are tightly linked to the corresponding control system objects. The operator can navigate around the model, investigate details, get an overview and clearly see the physical and spatial relations.

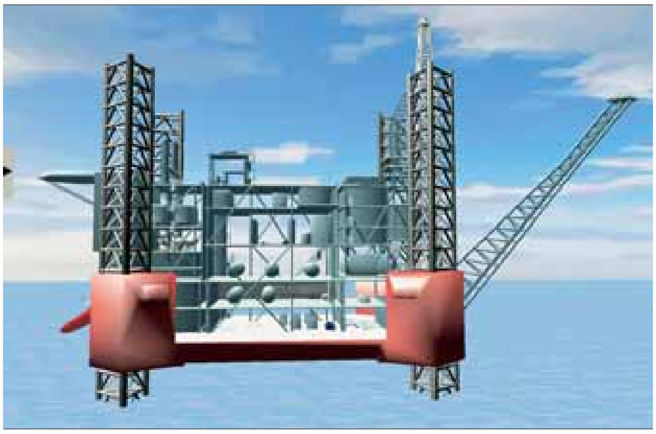
So what benefits does the introduction of the new dimension offer? A 3D interface is life-like, and hence easy to recognize. It shows relations and dimensions in an intuitive manner, and is well suited to the human mind. Humans are accustomed to perceiving objects, remembering locations and relations and orienting themselves in three dimensions. Even more, we are actually very good at it. It is more efficient to display complex information in three dimensions compared to traditional presentation techniques.

The advantages in using 3D models of the process and plant for operator interfaces in industrial control are apparent. By augmenting the process

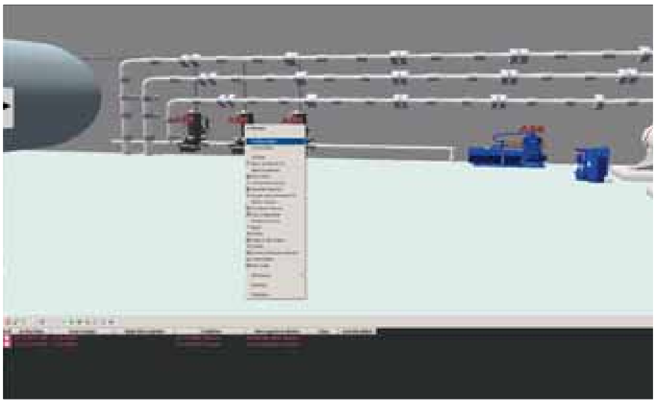
**Factbox** showing the strengths of humans and computers in decision making, based on Fitt's list.

| Humans are better at | Computers are better at |
|---|---|
| Perceiving patterns | Responding quickly to control tasks |
| Improvising and using flexible procedures | Repetitive and routine tasks |
| Recalling relevant facts at the appropriate time | Reasoning deductively |
| Reasoning inductively | Handling many complex tasks simultaneously |
| Exercising judgment | |

The 3D model provides an overview of the location of objects, personnel and other spatial considerations



Interaction with objects can take place in the same manner as in the traditional operator interface. The context menu gives access to all aspects of the component



control interface with a 3D-interface, many of the problems mentioned above can be overcome. The operator can get a better understanding of the situation, can be relieved of the mental stress of trying to understand the situation or remember the location.
A 3D representation can simplify collaboration. The physical limitations of what a field operator can and cannot do, the physical relationships between different objects and the location of components are immediately and intuitively understood when viewing a 3D representation of the plant. The operator does not need to have been on site or have to remember in which area the component is located. The interface shows it plainly and unambiguously.

**The operator must be able to switch effortlessly between the two representations to select the one which is most appropriate at that moment. There are distinct advantages in both interfaces that need to be clearly understood and taken advantage of.**

Furthermore, if the position of the field operator is known, for example through some tracking method, the advantages are even clearer. There is no longer any need for the operator to explain what she sees or where she is – such information is displayed precisely by the interface. Explaining one's exact position is not easily done on the walkie-talkie, especially if the control room operator or remote expert is not familiar with the location. When a critical situation arises, the seconds saved by this clear understanding of the situation can be of great value. More importantly, the chance of a misunderstanding is drastically reduced. As the control room operator can clearly see which component the field operator is facing, mistakes such as spelling mistakes or misinterpretations are much easier to detect.

The traditional process graphics cannot be done away with, nor is this an objective. A tight integration between the traditional process graphics and the 3D interface is crucial. The operator must be able to switch effortlessly between the two representations to select the one which is most appropriate at that moment. There are distinct advantages in both interfaces that need to be clearly understood and taken advantage of. For example, the traditional two dimensional interface is effective for showing a simplified and structured overview, while the three dimensional interface is better for seeing relations and understanding physical aspects of the process plant. A 3D environment is also better suited for navigating in large information spaces – a challenging task for the control room operators. Navigating between process graphics is a tedious task today, but the operators depend on being able to find what they are looking for quickly. By better supporting spatial awareness and providing efficient movement between distant locations, navigation can become natural and lightweight so that users can focus on solving the problem.

So, how distant is this future? ABB has developed a concept prototype that works inside the System 800xA framework. This is a necessary step to get valuable feedback from operators, customers, and internal sources. Understanding the true benefit of 3D interfaces can only be achieved through real-life testing and experimental investigation. The preliminary results show improved interaction for many of the problems faced by today's control room operators.

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# Mapping the weakest link

## New tools for visualizing the state of the power system

Mats Larsson, Reynaldo Nuqui, Linda-Maria Johansson, Stefan Bengtzing

Recent major blackouts have exposed the vulnerability of power transmission networks. Often such blackouts are caused or aggravated by the overloading of equipment. The resulting tripping shifts the overload to other lines. A rolling blackout can ensue with its negative consequences on the productivity of companies and the safety and comfort of people.

In most cases, the scope of the damage can be limited by operators taking the right decisions at the right time. This in turn requires information to be available in an easily accessible form.

ABB is bringing innovations to the control room. Graphical displays show the load on all lines and help identify the weakest links. Network topology is also matched with geographical and environmental data – operators can identify lines that are at risk of failing due to the weather or vegetation.

In most parts of the world, the demand for energy is increasing. However, the expansion rate of power networks is slowing, mostly due to environmental but also due to economical concerns. As a result, power grids all over the globe are more heavily loaded and are working harder than ever before. This means that margins with respect to equipment failure are shrinking.

Large power outages are usually the result of multiple component failures occurring within a timeframe of minutes, if not within seconds. Monitoring and control systems installed at utilities gather information from sensors within their own grid. They then evaluate this information to determine whether their network is operating in a state that ensures secure operation and delivers the power to meet demand conditions.

Most power system applications in use today report problems only on an individual component basis, such as line overloads, under/over voltage at specific points. Simultaneously, when things go wrong, power utilities are often dependent on operators taking the correct action to prevent an everyday event turning into a wide-spread blackout. Such an event can start with the outage of a single component, for example, a line or a transformer, and develop into a cascading series of failures, resulting in a severe outage.

A typical transmission grid may have thousands of lines and substations; a vast quantity of measurement data is collected during operation. Since it is impossible for an unassisted operator to grasp the information content of all this data in a timely manner, security assessment and visualization tools that distil the data into useful information are becoming increasingly important.

Large power outages are usually the result of multiple component failures occurring within a timeframe of minutes, if not within seconds.

These needs are underlined by the excerpts from the August 2003 North American Blackout Report [1] presented in the Factbox.

One part of the solution that is presented in this article, lies in achieving better situational awareness for power system operators. This can be achieved through tools that process power system measurements using advanced stability assessment and visualization techniques.

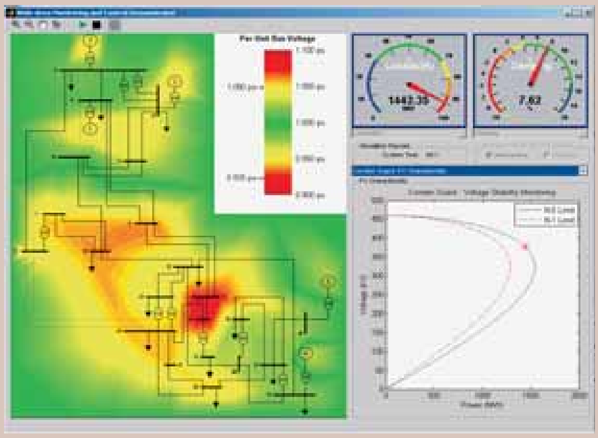
### Visualization of static power system data

ABB has a range of network management software based around SCADA (Supervisory Control and Data Acquisition) and state-estimation packages. These provide a detailed and accurate picture of the network with a time-resolution of seconds to minutes. This is sufficient for the analysis of all static aspects of power system operation such as reactive power balance and margins, component or transfer path loadability limits and voltage profiles.

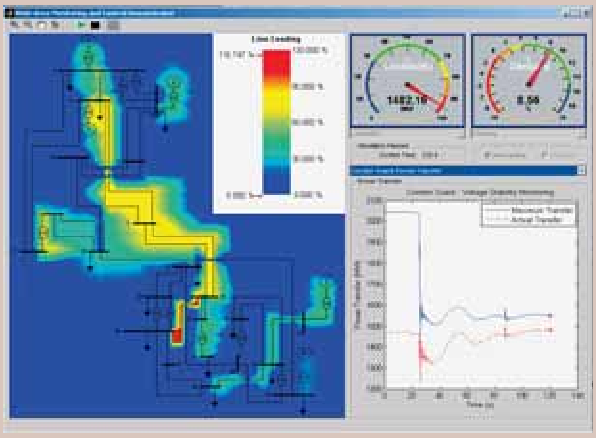
**Factbox** Excerpts from the August 2003 North American Blackout Report [1]

- **Observation** – "A principal cause of the August 14 blackout was a lack of situational awareness, which was in turn the result of inadequate reliability tools and backup capabilities."
- **Needed Action** – "Improved visibility of the status of the grid beyond an operator's own area of control would aid the operator in making adjustments in its operations to mitigate potential problems"
- **Observation** – "This resulted in an inability to detect, assess, respond to, and recover from IT system-related cyber failures (failed hardware/software, malicious code, faulty configurations, etc.)."
- **Needed Action** – "IT and EMS support personnel implement technical controls to detect, respond to, and recover from system and network problems."

**1** Visualizing voltage magnitudes through color contours – the red colored section in the center of the system identifies areas with an abnormally low voltage



**2** Visualization of line loading through a contour display – the color corresponds to the loading of each line relative to its capacity



## Capital productivity

Experience has shown that humans can absorb and analyze visual information much more quickly they can absorb numerical information [2]. Contour mapping of voltage, load or generation profiles can be used to visualize the system-wide operating conditions and help operators pinpoint trouble spots in the grid with just a glance at the screen. One example is depicted in 1, where voltage magnitudes are shown by color contouring. The red sections in the center of the system identify areas with an abnormally low voltage. Following a quick localization, more detailed numerical displays can be opened to further investigate the source and possible solution to an abnormal network situation. In a contour plot, the color indicates the severity of the threat and the locations in the contour maps correspond to the geographic location of the problem area. Compared to a conventional alarm or warning log which typically shows only the location as a text string, it is much easier for an operator to find a solution to the problem. More importantly, when there are deviations from the normal voltage profile in several locations at the same time, the color display can be used to rank the severity of the different threats to power system security and quickly select the best area to focus corrective actions on first.

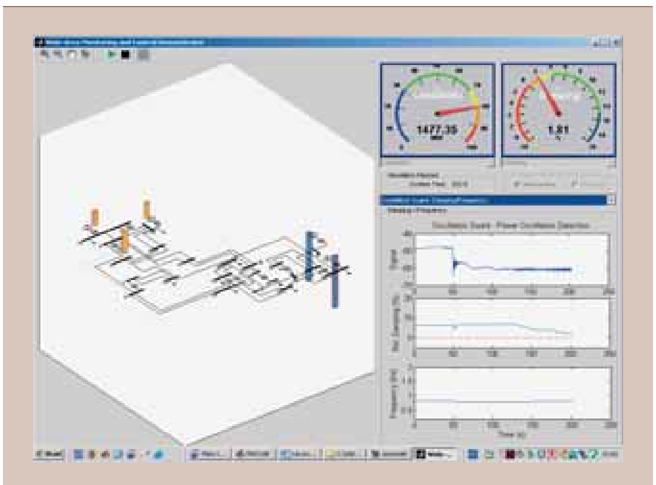
Once a trouble spot has been located on the contour map, an operator can take preventive action to ensure an abnormal situation does not progress into a system-wide outage. In the example of 1, the operator can disconnect load or insert additional capacitor banks or FACTS (Flexible AC Transmission System) devices to regulate reactive power and improve the voltage profile.

Contour mapping can also be effectively used to pinpoint overloaded components in the network. If such overloads are allowed to persist, most equipment must be fitted with local protection devices that will disconnect it with a time delay of tens of minutes. Thus, given the right information, operators can observe overloads in time and take corrective actions such as disconnecting load or reconfiguring the network before lines are automatically disconnected by overload protection, thereby preventing cascading failures and blackouts. 2 shows an example display where the color contour corresponds to the loading of each line relative to its capacity. The red colored section can be used to quickly pinpoint lines that are overloaded.

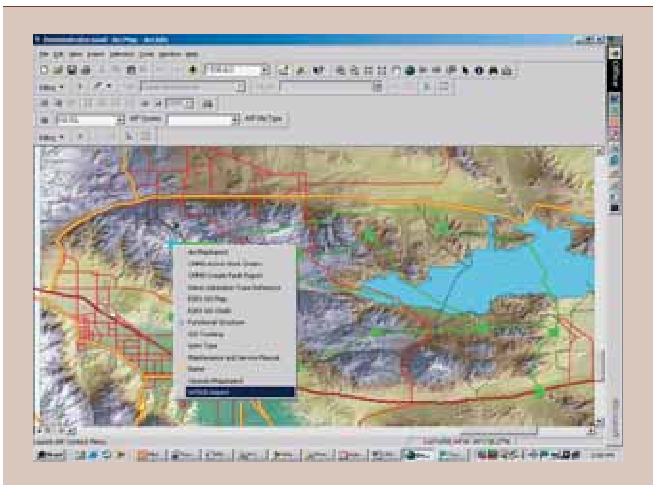
### Visualization of power system dynamics

New phasor measurement and wide-area monitoring system (WAMS) technology is able to provide data at a rate of 10-20 values per second. This ensures a response of the measuring system that is fast enough for the monitoring, not only of slow phenomena such as voltage and load evolution dynamics, but also of faster phenomena such as oscillatory, transient and frequency dynamics that are im-

3 Real-time visualization of frequency dynamics in 3-D with the generator speeds and results of oscillatory stability monitoring illustrated by bars animated in real-time.



4 Real-time visualization of electrical network overlaid with GIS shaded relief map and road network map layers



portant for the stability of the power system. However, because of the high time-resolution of the measurements, a WAMS will deliver huge amounts of data that needs to be properly processed for specific applications before being presented to the operator.

The phasor measurement data can also be analyzed automatically in a number of ways. Voltage stability monitoring uses measurements from both ends of a line or corridor that is known to be critical as far as voltage stability is concerned. It creates an equivalent model of the corridor and assesses the voltage stability of the system as often as 10–20 times per second. The output is visualized using the power-voltage characteristic shown in the bottom right portion of 1, with the current operating point illustrated by the red asterisk and the maximum loadability illustrated by the rightmost point of the blue curve (bottom right). The meter display marked "Loadability" also shows that the current loading is 92 percent of the theoretical maximum.

The monitoring of oscillation damping uses on-line estimation of an equivalent dynamic system model based on phasor measurement data. The model can be used to assess the stability of so-called inter-area oscillations that are becoming more and more common as networks are interconnected to span large areas. The damping is illustrated by the meter in the top right of 2. 3 shows a situation in which there is 1.8 percent damping of the dominant oscillatory mode. A negative damping would imply that the oscillation is unstable and could lead to a power system collapse. Typically, at least 6-7 percent damping is desired. When such a low damping as that shown here is detected, the operator must be alerted so that corrective actions can be taken.

Furthermore, 3 shows a 3-D visualization of frequency dynamics. The bars shown below the schematic in cool color tones (from violet to green) represent busses or generators where the estimated or measured frequency is below the weighted system average. The bars rendered above the schematic in warm color tones (from green to red) represent areas where the frequency is observed to be above the weighted system average. The figure clearly shows that the two generators at one end of the system oscillate as one group against the group of three generators at the other end. In this case the oscillation is close to being unstable – this is illustrated by the low damping shown on the damping meter at the top right.

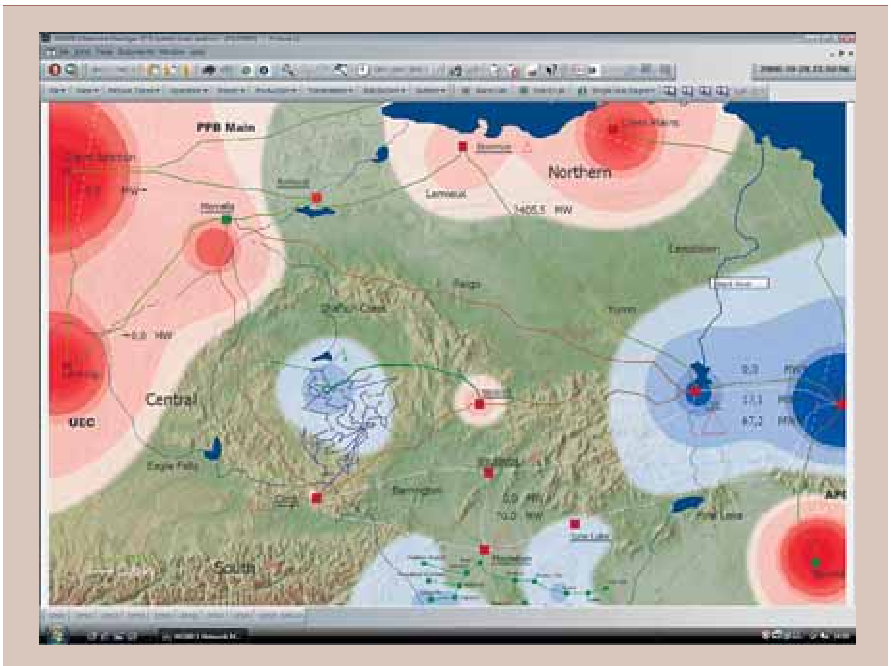
## Contour mapping can be effectively used to pinpoint overloaded components in the network.

### The role of GIS

GIS (Geographic Information Systems) enhance visualization of power systems by associating spatial data with transmission assets. They support a wide range of visualization options such as contouring and animation, making them attractive platforms for displaying geographically referenced real time power system data such as the voltage and line loading contours discussed above. GIS information is stored in geographical map layers making it easy to relate transmission network conditions with other relevant information such as weather, vegetation growth, and road networks. Real-time weather data integrated in GIS increases the operator's situational awareness. For example, with the help of such a system, the identification of a weather front moving towards a given area enables operators to quickly pinpoint transmission facilities with increased risks of outage. In conjunction with SCADA/EMS[1] data, the operator can then initiate dispatching orders to protect the system against potential cascading failures. GIS vegetation maps can be combined with real time line loading information to identify lines with increased risk of flashovers and faults due to sagging. Such lines can then be considered candidates in the EMS contingency analysis. Conversely, if the GIS vegetation map shows negligible growth, operators can push more power through a corridor with line-sag constraints.

GIS data can also enhance operator actions after disturbance conditions. Results from transmission line fault location devices can be translated into

5 The ABB Network Manager function, Dynamic Contour Coloring, monitoring deviations from nominal voltage levels – red areas signal high and blue areas low voltages



geographical coordinates to identify affected tower spans; this together with GIS data on terrain, vegetation, road networks, and weather conditions enables operators to quickly estimate the time required for repairs. The time to repair plays a critical role in deciding whether an operator should issue costly unit start-up/shut-down orders. In major storm events, GIS maps displaying the relative geographical locations of line and tree maintenance crews assist operators in deciding which parts of the power system can be quickly restored to minimize customer outage time.

GIS data can be made available to operators via cross application navigation with SCADA/EMS systems.

4 shows a GIS interface displaying an electrical single line diagram with geographical-based maps and road networks. Assuming that a GIS object representing a substation has changed color and starts flashing, indicating an alarm; the operator can then right-click on the GIS object to bring up a context menu allowing him to navigate into the ABB NM WS500 interface for that substation. In the WS500 interface, the operator finds that the alarm indicates a breaker fault and acknowledges it and then sends out a maintenance order. The operator then right-clicks on the breaker, navigates back to the GIS interface and quickly views the road network around the substation. The operator can then order a re-dispatching of generation and transmission facilities based on the new operating conditions resulting from the outage.

The geographical information from the GIS data can also be combined with the contour mapping of the electrical state as illustrated in 5 (showing a screenshot from the ABB Network Manager). Here a relief map imported from a GIS is shown together with a network diagram. The voltage profile is shown as a contour map.

**Geographic information systems enhance visualization of power systems by associating spatial data with transmission assets.**

### From the research labs into the ABB SCADA systems

Visualization of power system dynamics is still an important research area in which new visualization techniques will emerge in order to further improve situation awareness in power system operation. But techniques are now also finding ways out of the research labs into the ABB SCADA systems used for geographically distributed processes.

The ABB Network Manager system now supports a function using the dynamic contour coloring technique. This is shown in 5 – the WS500 operator station shows a zoomable world map with a geographic process overview. The dynamic contour coloring layer is semitransparent and may, as in this figure, be superimposed on a GIS map layer retrieved from a web-based GIS map server. Real-time information is overlaid over the GIS map and the dynamic contour colored image. Aspect object navigation can be used to navigate to asset and maintenance management systems, for example.

A model of the ABB Network Manager control room

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Footnote

1) SCADA: Supervisory Control And Data Acquisition (a large-scale, distributed measurement and control system) EMS: Energy Management System (a system of computer-aided tools used to monitor, control, and optimize system performance)

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# The drive for simplicity

## Progress in AC drives technology make life easier for operators

Ilpo Ruohonen, Mika Pääkkönen, Mikko S. Koskinen

ABB offers one of the world's largest portfolios of AC drives, serving an expanding horizon of applications. With increasing demands for flexibility, reliability and ease of use, ABB has come up with a number of solutions to make life simpler and cheaper for its customers.

By combining functions and cutting part counts, ABB has reduced the size of its drives while enhancing their reliability. The company has also developed a simplified set-up procedure using a harmonized keypad and software wizards that can be used across the ABB drive family.

More complex programming can be carried out using ABB's Adaptive Programming utility and parameters can be transferred between drives using ABB's patented FlashDrop technology.

All these advances are part of an on-going effort at ABB to offer cutting edge technology in high performance, yet user-friendly systems.

Traditionally, the primary use of drives has been in such applications as powering pumps, fans and conveyors. And while they will continue to be used in these applications, today's end-users have a very different approach to that of a decade ago.

Drives are now fully developed and are therefore more widely accepted as a product. The need to answer the question, "what does it do?" has been replaced by the expectation that the drive will "just do it". This shift in attitude brings with it the assumption that the drives are simple to buy, simple to install, simple to start-up, simple to commission and simple to own and run.

At the same time, drives are finding new applications: in exercise machines, pizza ovens, honey centrifuges and car washes. In these applications, the drive is very definitely considered a commodity, and the original equipment manufacturers (OEMs), who may not traditionally have used drives, are once again demanding pure simplicity. In fact, a recent survey [1] showed that simple controls and set-ups (70 percent) and convenient operator interfaces (53 percent) were rated as "very important" by AC drives users.

### The quest for miniaturization

Simplicity and ease of use manifest themselves in many ways. The mere fact that drives can now be used in domestic washing machines is a testimony to their extreme compactness. Drives have become smaller, more capable, easier to use and cheaper, by orders of magnitude.

Smaller drives are easier to install. Panel builders are able to fit more drives into a standard cubicle, so the whole panel can be smaller. This allows the use of smaller and less costly control rooms. It also becomes easier for OEMs to fit drives into their equipment. A classic example of this is in cranes, an application that has always had very limited space for the drive.

The reductions in drive size have resulted from the use of fewer components, greater packing density, improvements in semiconductor technology and improved cooling techniques. In fact, there has been a ten-fold decrease in the size of drives over the past 10 years.

### Driving down cost

An additional benefit of reducing the component count in a drive is that it cuts costs. ABB predicts that, over the next few years, the parts count of its drives will be reduced by approximately 20 percent through the use of integrated electronics to eliminate separate components such as external flash and RAM memories and analog/digital converters. Mechanical parts are also being integrated, for example, by combining frames and enclosures, allowing them to perform multiple functions.

> There has been a ten-fold decrease in the size of drives over the past 10 years.

Reducing part count also enhances reliability: fewer parts mean fewer interfaces and fewer mechanical fixings, which are often a source of failures.

### Improved cooling

Advances in the development of power semiconductors have also helped to improve drives. A reduction in the power losses per unit area of silicon used means that the same silicon area is able to handle more power. This has enabled smaller semiconductors and reduced the need for cooling within the drive. This, in turn, allows the use of smaller heat sinks and reduced air volumes inside the drive – the result is smaller and smaller drives. The only limitations are the terminals because these must accommodate cables that are large enough to carry sufficient current to the drive.

But it is not just the development of power semiconductors that has enabled miniaturisation of drives. Of prime importance is the technology used for cooling. Considerable R&D effort is being put into developing new cooling techniques, as well as into reducing the need for cooling.

While air cooling is likely to remain the dominant technique, liquid cooling is finding increasing use in areas such as wind power, transportation and marine applications, as reflected by the recently launched, liquid-cooled ABB industrial drive.

### Increased functionality

These ever-shrinking drives contain ever-expanding functionality – thanks to developments in software. Today's software monitors, diagnoses, configures and archives information and parameters concerning drives in industrial plants.

Set-ups are performed entirely using software functions, and then downloaded to the appropriate drives. The set-up information is archived for future retrieval. To obtain the full benefit of this technology, however, operators must still refer to the user manual. ABB is striving to develop intelligent control panels that will

1 The ABB standard drive keypad allow all functions and parameters to be set up with only eight soft keys


2 FlashDrop, a patented new technology that streamlines the drive configuration process.

significantly decrease the need for paper-based manuals. The secret, though, is to find an easy way of accessing this kind of functionality. Enter the keypad 1.

### The ideal keypad

ABB's R&D team scrutinized every aspect of how a user interfaces with a drive and developed what it believes is the most user-friendly keypad ever. The keypad for the ABB standard drive features only eight soft keys, through which all parameters, functionality and set-ups can be accessed.

Even the actual buttons on the keypad were carefully selected to ensure that just the right level of built-in resistance gives the user the feeling of stability and accurate key-press detection.

To develop the keypad, ABB compiled 11 guiding usability principles that consider all aspects of visibility and readability; the type of text and terminology, and the icons used. Based on this, ABB is now harmonizing the keypads of all of its drives. A common look and feel allows the users to switch between different ABB products easily, without having to go through a time-consuming learning process for each new product.

### The true value of the keypad

The advantages are not all aesthetic. There is a real financial incentive for customers to choose this keypad and its intuitive commands. Most equipment investment decisions now carry a proviso for fast installation to ensure that production will start rapidly and smoothly. Paramount is the speed with which a machine can be up and running after the installation of new equipment or after a maintenance shut down. If a machine breaks down, it can cost the operator $20,000 per hour, so easy set-up and commissioning are a priority. Such urgency increases the risk of errors in installation and commissioning. These can be overcome by eliminating manual intervention wherever possible; the keypad is central to this aim.

These guiding principles, and the fact that there are only eight keys on the keypad, suggested the need for intuitive assistance. ABB developed a series of "wizards" aimed at guiding the user through various procedures. There are "maintenance assistants", "diagnostic assistants" and, one of the most widely used, a "start-up assistant".

### The magic of wizards

With the start-up assistant, ABB provides a tool that guides the user through both start-up and commissioning by asking questions in plain text language. There are no complex parameter numbers or codes. The product's intelligence helps the user through the commissioning process.

For an OEM, who might buy 4,000 AC drives per annum, the time saved by using an easy start-up system such as ABB's wizard can be significant. It can cut 15 minutes from the commissioning time of each drive, equating to a time saving of 1,000 hours per annum. For an engineer working 2,000 hours per annum, this is half a man-year.

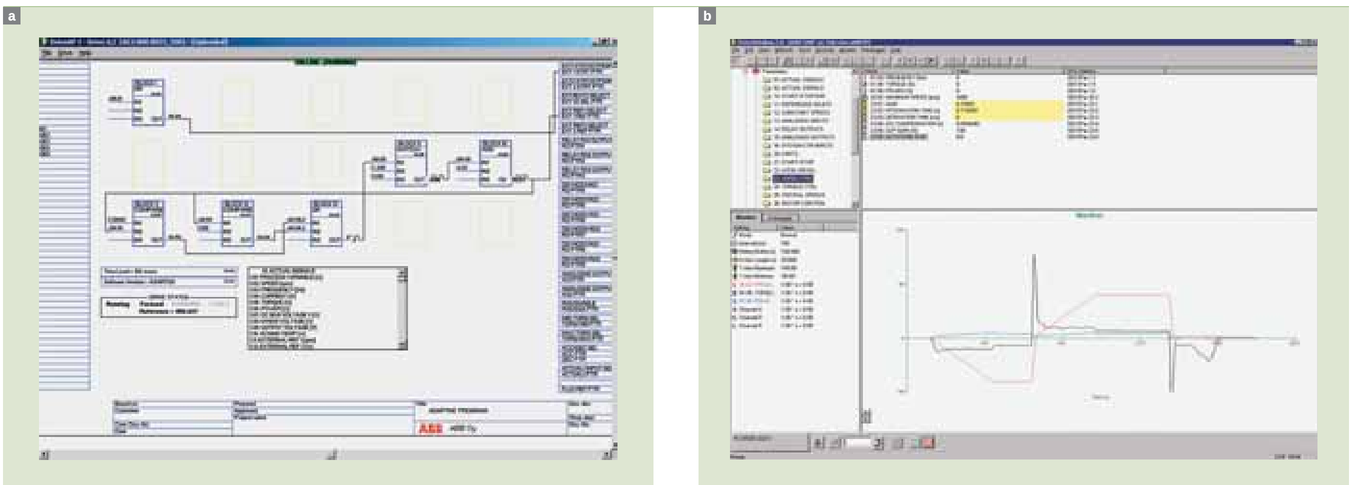
A common look and feel allows the users to switch between different ABB products easily, without having to go through a time-consuming learning process for each new product.

### Specialist HMI

Another tool that makes life easier for the OEM is a hand-held human-machine interface (HMI) that allows drive parameters to be installed in seconds. Called FlashDrop and available with selected ABB drives, the device can be used to select and set parameters, and to copy configurations between drives, without even powering up the drive 2.

FlashDrop is a patented new technology from ABB that streamlines the drive configuration process, allowing users to download a set of parameters in just two seconds. No specialized knowledge is required to use FlashDrop and the user interface will be familiar to users of ABB drives.

3 ABB's Adaptive Programming utility: configuring operations from a predefined set of functions



## Ease of use

While the HMI is clearly important, ABB has also been looking at ways to simplify customer applications using the functionality packed into a drive. One of the drivers is the customer's interest in total cost of ownership, which includes commissioning, swap-outs and maintenance.

### Application-specific solutions

AC drive users can now reduce costs even more by employing application-specific drive solutions. These drives incorporate incremental functionality that supports specific applications such as fan and pump control, mixers, or crane controls. They can reduce the total cost of ownership through shorter start-up times, lower integration costs, and improved machine productivity.

Time savings during commissioning can range from one to several hours The process does not require expert programmers and therefore saves the considerable expense of sending commissioning engineers around the globe to fine tune individual drives.

Take, for example, ABB's new pump control software module, Intelligent Pump Control (IPC), which eliminates the need for an external PLC (programmable logic controller) and can help to save energy, reduce downtime and prevent pump jamming and pipeline blocking.

The IPC is a software add-on for ABB industrial drives. It contains all the common functions needed by water and waste utilities, industrial plants and other pump users through six pump control functions.

The software also incorporates ABB's adaptive programming utility 3, enabling users to customize drives for specific applications. This utility consists of a set of simple to use blocks that can be programmed to perform any operation from a predefined set of functions. All common mathematical and logical functions as well as switches, comparators, filters and timers are available. These days, users can have the power of a small PLC inside their drive in the form of ABB's Adaptive Programming.

A further breakthrough is that programming can be carried out using the standard control panel. No special hardware or software programming tools are needed. As a result, the programming takes only a few minutes and can be carried out on-site, during commissioning.

### Technology that stands the test of time

Even well established technology does not stand still. It is now 11 years since ABB launched its revolutionary motor control platform, Direct Torque Control (DTC). Now the algorthims have been tweaked in order to move standard AC drive technology into the servo arena. The result is the launch of the ABB machinery drive.

The drive uses standard AC drive technology, but, by tuning DTC to include a motor model designed for servo motors, and by using very fast torque control loops within DTC – along with some other clever design work – the drive can now reach servo drive performance levels. It can control synchronous or asynchronous motors, either open- or closed loop. With the new drive, depending on the application, machinery builders need specify only one drive for a variety of motor types along with an appropriate feedback device.

### Three modules

Despite their significance, the advances described so far are only half the story. The ABB machinery drive features another significant major breakthrough aimed at meeting head-on the challenges faced by OEMs. This is the use of three plug-in modules that house the heart and brains of the drive. On the hardware side, there is a power module and a control interface module, while the software module provides easy programming of the relay logic or PLC routines that an OEM may require for its own applications. It is the way in which these modules are used that will reduce commissioning times, eliminate the need for external maintenance engineers and minimize unpredicted production line stoppages.

By providing separate units, both the power module and control interface can be shipped to site and installed ahead of the software memory unit. When the installation is complete, the memory unit, which can be programmed on the OEM's own premises with specific application code, can be delivered and simply plugged into the control interface on site.

The modular approach also allows the number of product components and variants to be reduced.

Since there is no need for on-site programming or the connection of any communication cables to PCs, time savings during commissioning can range from one to several hours. The process does not require expert programmers and therefore saves the considerable expense of sending commissioning engineers around the globe to fine tune individual drives.

### The future

AC drives are set to be smaller, more intelligent, easier to install and control, have better communications, and be suitable for many more applications – particularly at the low power end of the range – all at a constantly reducing price. What better future could drive users ask for?

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# Ambient intelligence

## Wired environments keeping the human firmly in the loop

Nils Leffler

Homes and offices epitomize the integration of the *human in the loop*. Technology is being used more and more to provide for comfort, entertainment and security needs, and to enhance productivity. During office hours, workers rely on modern computer technology to provide a whole range of services, from e-mail to electronic reservation systems for rooms and equipment. Such services must function efficiently in an integrated network, allowing users in different locations to communicate with one another and access centralized resources. At home, the simple act of recording a favorite television program should not involve hours of pouring over complicated user manuals. Design requirements for intelligent devices are dominated by ease of use, but they also include reliability, energy efficiency and affordability. New technologies are being wired into homes and offices to provide ambient intelligence, with the human clearly in the center.

## Ease of use

Ambient intelligence refers to an emerging technology that "will increasingly make our everyday environment sensitive and responsive to our presence" according to a recently published book [1], it will transform homes and offices into "intelligent" environments. "This vision requires technology invisibly embedded in our everyday surroundings, present whenever we need it that will lead to the seamless integration of lighting, sounds, vision, domestic appliances, and personal healthcare products to enhance our living experience". Lights will be switched on and off, and blinds will be moved up in response to a range of stimuli, including human activity. Such automation will provide enhanced comfort and productivity, and will reduce energy consumption. It will also provide better communication and security.

Ambient intelligence refers to an emerging technology that "will increasingly make our everyday environment sensitive and responsive to our presence".

In keeping with the modern trend for user-friendly intelligent technology, ABB's company, Busch-Jaeger Elektro GmbH, has launched easily programmable touch sensitive display units 1 combined with a range of motion sensitive switches 2 and alarm units under the brand of "Smart&Lean". These products can be incorporated into networks to control everything from music and lighting to blinds and security alarms. The units monitor human activity using infrared motion detectors, and each has a number of operating modes to satisfy the specific needs of its allocated area. These adjustable modes range from fully automated to fully manual. Heating and cooling functions can be integrated into the system alongside lighting controls, with individual thermostat settings being specified via the central display unit. Key to the success of these devices is their ease of use, combined with elegant design 3 and longevity.

Lighting settings need to be controlled for a number of reasons. Aside from creating the right ambience at a dinner party, building managers may want to reduce electricity consumption by installing timed off-switches in corridors and other communal areas. Or they may want to reduce the risk of accidents by providing motion-sensitive on-switches in dark stairwells. Whatever the reasons, programming the appropriate settings must be quick and easy, and more than one setting must be available. A reading room and a living room have very different lighting requirements. But what if the reader wants to read in the living room? The change from one condition to the next should be achieved by the touch of a single button.

The integration of a music system under similar control would further enhance the desired ambience in a room. The incorporation of a service record, listing of maintenance schedules and equipment renewal dates, would enhance the efficiency and safety of many buildings.

### Safety and security

For most people, home is a sanctuary in which peace of mind resides. Unfortunately, this is not universally true and demand for better home security systems is increasing. The integration of additional functions alongside ambience settings in an intelligent environment can provide considerable benefits to the home owner. Such features are now easing their way onto the market. Functions include "door unlocked" and "window left open" warnings and alarms for security motion detectors 4, along with the more standard alarms and audio features. A more advanced feature allows lighting and blind settings to be recorded in a home over a week of normal occupancy. This sequence can then be replayed during periods when the home is unoccupied. The "simulated presence" provided by this function gives the absent occupier a feeling of comfort, knowing that the house appears to be in use. The application of video surveillance equipment takes security monitoring to a higher level, even allowing remote surveillance of properties.

### Energy efficiency in the future

As demand for electricity continues to grow, periods of peak load are becoming more difficult to handle. To avoid black outs caused by excessive demand on limited supplies, electricity generators offer cheaper tariffs to encourage off-peak use. By incorporating this information into the integrated control systems of homes and offices, significant savings can be made. On a larger scale, control systems of the future will allow functions to be prioritized so that non-essential services can be reduced or suspended

1 Display unit – house overview

2 Movement sensitive switch

3 Display unit – profile

4 Alarm unit

5 Display unit – house panel, drilled down to a single room

when the risk of network overload is imminent. To implement these features, each individual appliance must be accessible remotely and low-priority appliances must be distinguishable from more essential equipment such as alarm systems, computers and freezers. This will allow electricity providers to define schedules for each level of equipment, and to shed loads accordingly. The same information bus used for the integration mentioned above would provide the backbone necessary for such energy efficient use of equipment.

### Technology from Busch-Jaeger

The Busch-Jaeger system is centered on a fully graphical, LCD panel 1. The touch-sensitive panel is used to display and operate up to 210 switching and control functions via overviews and drill-down screens. The screens define individual rooms or areas 5 and can be configured to meet the needs of individual end users.

The information bus, on which the system is based, is the ABB i-bus EIB. For programming and commissioning purposes, a multimedia/SD (secure digital) card is the preferred medium, but modifications can also be handled via the EIB bus and a simple computer-EIB interface (RS 232 or UBS).

The infrared motion detector in each Busch-Jaeger comfort switch has a range of 170 °C, so little escapes its attention. The switches use two-wire technology combined with an external input to provide convenient integration into any cross-connection. The system is inherently safe and can be installed with minimal disruption to existing services.

**The “simulated presence” provided by this function gives the absent occupier a feeling of comfort, knowing that the house appears to be in use.**

### Conclusion

The intelligent building is gradually becoming a reality, but its success depends on the development of systems that are easy to use. ABB Busch-Jaeger has taken on this challenge and launched a range of Lean&Smart devices that can be networked to control lighting, blinds, screens, room heating and cooling, alarms and intercoms. Embedded sensors measure temperature, light levels, wind speed and human activity, giving rise to audible/visible alarms or mechanical responses. The network is based on the ABB’s i-bus EIB that allows the integration of environmental control, entertainment and security systems, and more. It is configured via a user-friendly, ergonomically designed touch panel through a series of easy to read screens.

**Busch-Jaeger Elektro GmbH, has launched easily programmable touch sensitive display units combined with a range of motion sensitive switches and alarm units under the brand of “Smart&Lean”.**

The system operates under the guiding principle that technology should serve the user – not the other way around. This guarantees that ambient intelligence will enter homes and offices unobtrusively, relieving the human occupants of tedious responsibilities, while keeping them firmly in charge of the loop.

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# Room for improvement

## Identifying limiting factors in process industries

Andreas Kroll, Frank Simon, Gordon Cheever, Tomi Pilbacka, David Stanier

Processing plant operators are under constant pressure to increase profitability. An important first step to securing competitiveness is to understand how an individual plant compares with that run by the most efficient operating authorities. Despite the variation between different plants, this can be done using industrially accepted performance indicators.

When plant improvement projects are initiated, an important challenge is to identify opportunities likely to yield the highest improvement impact. A possible selection criterion is to choose an area based on the assessor's personal experience, and carry out an initial survey. Typically this would be followed by a focused techno-economic analysis to estimate the improvement potential. Often, a performance baseline is established in order to measure the effect of the improvement projects.

**The principle of this top-down procedure is to search for improvements across disciplines, functions and components.**

This article presents an alternative approach that broadly screens automation systems and working practices in the process industry for improvement potential[1]. The screening is functionally limited to the assessment of:

- on-line process automation and information systems
- instrumentation and analytical devices, motors and drives
- motors and drives which will be referred to as „I&C" in the following

The newly developed, computer supported, systematic procedure enables the assessor to screen a plant in just a few days. Firstly, a complete technical evaluation of installed systems and equipment as well as working procedures is made. Secondly, the economic improvement potential of increased throughput and cost savings is estimated by comparison with the performance of world-class plants.

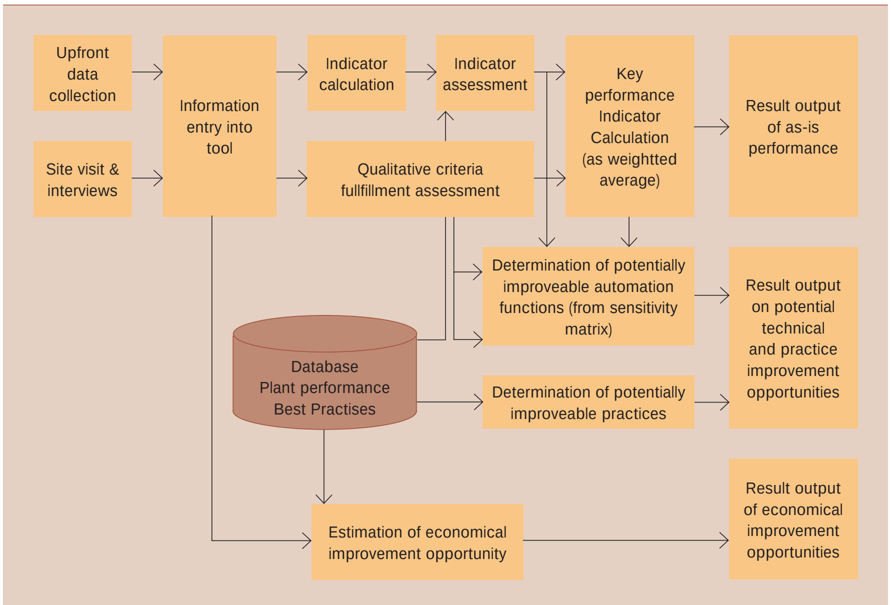
The principle of this top-down procedure is to search for improvements across disciplines, functions and components. Typical questions include: "Do reduced maintenance costs have a higher impact than the implementation of advanced process control (APC), or would better support of operating-point and product changes have a higher economic impact?"

An interdisciplinary team has developed a process for rapidly screening I&C systems and components and related working procedures by combining assessment and benchmarking methods. The new method, which requires a site visit of only two to three days, has been tested in pilot applications in the chemical- and pulp and paper industries.

## Methodology

An overview of the individual steps and the required data processing of the developed methodology is provided in 1.

1 Steps in information collecting and processing




## Assessment and benchmarking

Assessment denotes the act of determining whether items, processes, or services meet specified requirements. In this article, the term assessment refers to the evaluation of plant performance using predefined measures. An important, though difficult, task is the identification of the maximum achievable performance value, ie, when exactly 100 percent performance is achieved.

Ahmad and Benson [2] defined benchmarking as a structured process to compare the performance of a plant with the best similar plants worldwide. The underlying objective is to learn from the best in the class. Some assessments even make comparisons between different industries. In this article, benchmarking refers to the comparison of a plant with other plants in order to rank its performance. This ranking procedure will identify whether a plant performs better than average and whether it falls within the top 25 percent best performers of the chosen comparison set. Comparisons can be conducted on a global or regional basis, cross-industry or within an industrial sector, or they can be based on other criteria.

**An important, though difficult, task is the identification of the maximum achievable performance value, which does not necessarily equal the theoretical 100 percent performance.**

## Hierarchy of performance and key performance indicators

Process automation is broadly scrutinized during the technical evaluation. This identifies the most significant issues for further detailed analysis in the follow up engineering study.

The spectrum of assessments ranges from instrumentation, through control systems and APC, to production scheduling and maintenance management systems. The assessment considers the technology, its utilization,

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working procedures, and operational and maintenance costs.

Approximately 100 criteria, some qualitative, others quantitative, have been identified. Quantitative criteria are defined as *performance indicators*. Some examples are shown in the Factbox.

Qualitative criteria are defined for different performance levels and provide a means by which to carry out consistent, reproducible and comparable assessments. All these criteria are aggregated into ten key performance indicators (KPIs), highlighting subgroups of areas that may require improvement.

1. Instrumentation and control (I&C) asset condition
2. I&C life cycle (obsolescence)
3. Throughput
4. Quality and yield
5. Flexibility / agility
6. Environment, safety and compliance
7. Maintenance
8. Operational costs
9. Personnel
10. Operator support

### Assessing the performance indicators

Once the performance indicator values have been computed, they must be assessed. Each is evaluated to determine whether the process performance is already at a good level or whether there is a significant opportunity for improvement.

The scale of each performance indicator can be different, but a common scale makes the interpretation and correlation of KPIs easier. For this reason, four performance indicator reference levels were defined:

- World-class performance (Score = 4)
- Good performance (Score = 3)
- Intermediate performance (Score = 2)
- Significant improvement potential (Score = 1)

In order to determine the boundaries between these four levels, an ABB database with more than 300 performance assessments, together with results from industry councils and publicly accessible literature, were evaluated. The experiences of ABB experts were also taken into account. This expertise comes from a variety of sources, including ABB's large portfolio of automation products, many grassroots and modernization projects, and full service contracts for many plants.

To simplify processing, a non-linear scale was introduced to score each performance indicator. This harmonizes the different scales used to assess each performance indicator, mapping the result to a common scale (1 to 4) for all performance indicators.

2 The result example shows the 10 KPIs with the achieved score percent and score points, respectively, and the lowest score (in points) of the supporting performance indicators

| Assessment Aspect | Score percent (0–100%) | Score points (1–4) | Min score (1–4) |
|---|---|---|---|
| I&C Asset Condition | 33% | 2.0 | 1.5 |
| I&C Life Cycle (Obsolescence) | 42% | 2.3 | 1.5 |
| Throughput | 32% | 2.0 | 1.0 |
| Quality and Yield | 59% | 2.8 | 1,5 |
| Flexibility / Agility | 35% | 2.0 | 1.0 |
| Environment, Safety and Compliance | 40% | 2.2 | 1.0 |
| Maintenance / Sustainability | 51% | 2.5 | 1.0 |
| Cost of Operation | 24% | 1.7 | 1.0 |
| People / Sustainability | 63% | 2.9 | 1.8 |
| Operator Support | 46% | 2.4 | 1.0 |

Factbox Quantitative criteria are defined as performance indicators. Examples include:

ACUI = Automatic Control Utilization Index

$$:= 1 - \frac{\text{Number of control loops designed for automatic but operated in manual mode}}{\text{Number of control loops designed for automatic mode}}$$

QCDI = Quality Control Degree Index

$$:= \frac{\text{Number of on-line measured and controlled product quality parameters}}{\text{Number of product quality parameters}}$$

ARSI = Average Alarm Rate in Steady Operation Index

:= Number of alarms received in 10 minutes

AMCI = Automation Maintenance Cost Index

$$:= \frac{\text{Maintenance cost for Automation}}{\text{Estimated replacement value of Automation}}$$

The critical success factors that make up each of the ten KPIs are computed as a weighted average, so that the proportional relevance of each component is taken into account. This results in a score on a scale of 1 to 4 and a percentage performance rating. An example calculation in tabular form is given in 2. The first KPI (I&C asset condition) has a percentage score of 33, or a score of 2.0.

**Combined performance indicators can be superimposed on the matrix elements to indicate which automation applications, components and systems are most relevant to improve operations.**

Applying a weighted average score to calculate KPIs can, however, mask individual components that are underperforming. To draw attention to such cases, the component with the lowest score is displayed as the Min Score. For example, the KPI throughput in 2, has an intermediate perform-ance score of 2.0 with a min score of 1. This suggests that at least one component of the KPI has significant improvement potential.

### Identifying targets for improvement

The technical assessment recognizes the strengths and weaknesses of a plant and identifies areas with potential for improvement. Depending on which automation-related system, application or practice is changed, the different performance categories are improved to different extents. For example, analyzers tend to affect yield and product quality. The reliability of systems can be improved by condition monitoring, while energy management systems have a particular influence on energy costs.

The sensitivity of (automation) drivers and (performance) results can be summarized as a generic sensitivity matrix 3 that can be read in two directions:

- The key automation areas for improving selected performance measures can be determined in a focused manner.
  (Effect area → Systems / components / applications)
- Where automation is missing, or working sub-optimally, the most affected areas can be identified and studied in more detail. (Systems / components / applications → Effect areas)

Combined performance indicators can be superimposed on the matrix elements to indicate which automation applications, components and systems are most relevant to improve operations. This highlights a subset of factors that can be studied in more detail. An example is shown in 3: The red cells contain large numerical values, indicating that the associated automation issue is highly relevant to the linked improvement issue. The numbers in the cells represent the *relevance* or the *strength* of the *association* and not the performance itself (as in the case of performance indicators).

## Economic improvement potential

Technical improvements are a means to an end: improved safety, sustainability and profitability of plant operations. Two typical economic objectives are increased throughput and reduced costs. The potential for improvement by increasing throughput can be estimated from an OEE (overall equipment effectiveness) loss analysis. OEE is expressed as a percentage and is defined as:

OEE = availability × production rate × quality rate

This measure is acknowledged as a best practice performance indicator. It compares current production with maximum possible production. The latter is achieved when a plant runs constantly at maximum capacity with no reduction in product quality. 4 shows an example of an OEE loss graph for a paper machine.

ABB holds databases with assessment results for different industries, including chemical, metal and mineral, and pulp and paper. The data sets can be classified by region, industry, type of operations, etc. This allows a selected plant to be assessed against a suitable sample.

The data provide demonstrated examples of excellent industrial performance and an indication of how performance can vary 6. This can be used to assess the potential for economic improvement and to rank a target plant within the sample set.

3 Excerpt of the sensitivity matrix of (automation) drivers and (performance) effects for an example assessment: Red cells (circled) indicate areas with improvement potential

| | Product / Application | Improvement Area / Driver | | | | |
|---|---|---|---|---|---|---|
| | | Process Yield / Efficiency improvement | Throughput / Capacity / Production rate improvement | Process Quality improvement | Energy & utility cost reduction | Plant agility improvement |
| Instrumentation & Control | Instrumentation – sensors & transmitters | 1.6 | 1.8 | 1.9 | 2.1 | 1.6 |
| | Instrumentation – control valves and positioners | 1.6 | 1.8 | 1.9 | 2.1 | 1.6 |
| Motors & Drives | Motors, Drives, Motor Control Center | 1.3 | 1.3 | 1.3 | 2.9 | 1.3 |
| | Analyzers of software property estimators / inferential measurements | 2.8 | 1.8 | 2.8 | 1.8 | 2.0 |
| | DCS – kernel i.e. Information and control (system type & size suitable for plant) | 2.2 | 2.0 | 2.2 | 2.1 | 2.0 |
| | SCADA & RTUs | 1.0 | 1.5 | 1.3 | 1.4 | 1.6 |
| | MES integration with DCS | 1.2 | 2.0 | 1.3 | 1.4 | 2.3 |
| | LIMS integration with DCS, QCS and PIMS | 2.2 | 2.0 | 2.2 | 1.4 | 2.3 |

## Ease of use

The potential for cost savings (both fixed and variable) is of particular interest when a plant's operations are limited by the market rather than by production efficiency. The cost factors to consider include energy consumption, maintenance, and personnel. Improvement opportunities can be estimated by comparison with world-class benchmarks.

### Software support tools

A software tool was developed for process plant assessment. The application guides data entry and conducts most of the analysis automatically. Computer support for assessing and benchmarking provides easy access to the integrated know-how and experience of many specialists. Furthermore, it ensures that assessments are carried out in a systematic man-ner. This improves consistency and reproducibility of results. The probability of making errors during data processing is reduced, allowing the assessor to focus on the primary tasks.

Without computer support it would also be difficult to conduct a broad assessment of a plant's performance within such a short time with a staff of only one or two people.

### Procedure

For increased efficiency, the assessment procedures were standardized. The process is summarized from a project per-spective below (see [1] for an outline of the methodology):

1. The scope of the assessment is agreed upon with the customer.
2. The plant receives a data collection form upfront.
3. The assessor conducts a short on-site visit, following a preagreed schedule that includes a plant tour and staff interviews.
4. The collected information is analyzed and benchmarking conducted.
5. The analyses result in the performance assessment and an overview of improvement opportunities.
6. Optionally, technical and economical improvement opportunities can be investigated in a more detailed study.
7. As an option, a follow up project can be initiated to ensure that the specified improvement opportunities become a reality.

### Pilot applications

Pilot studies using the methodology and the supporting computer software described in this article have been conducted in several industries: a continuously operated chemical plant, a plant for recycling wastepaper and some paper machines.

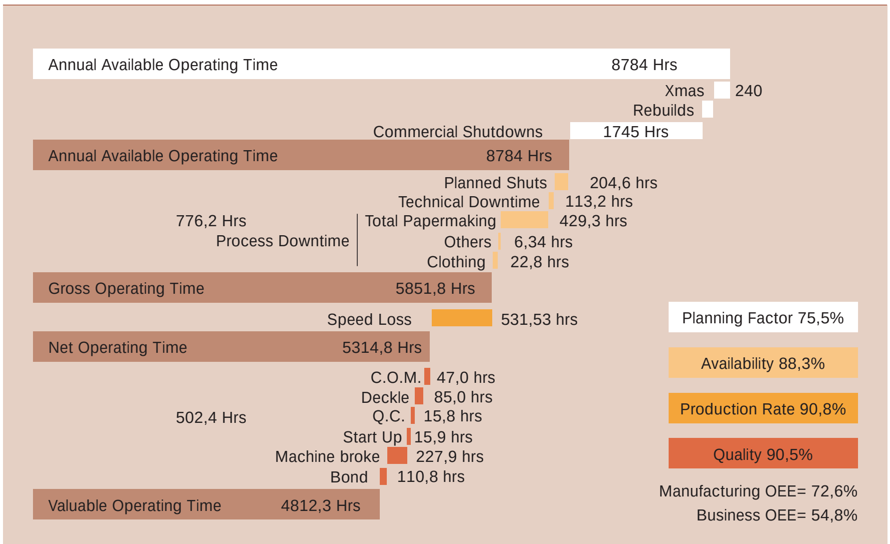
The plant operators provided the relevant production and financial data, and site visits of two to three days followed. In order to get a comprehensive view of the plant, interviews were carried out with panel operators, automation engineers, maintenance personnel, production planners, controllers, and the plant manager. With the help of the I&C assessment method and software tool, it was possible to assess the plant, rapidly, systematically and structurally, to obtain a full picture of the automation performance. Different functional areas were integrated in the assessment and a full view of the plant's performance was gained, showing its strengths and weaknesses.

**Computer support for assessing and benchmarking provides easy access to the integrated know-how and experience of many specialists.**

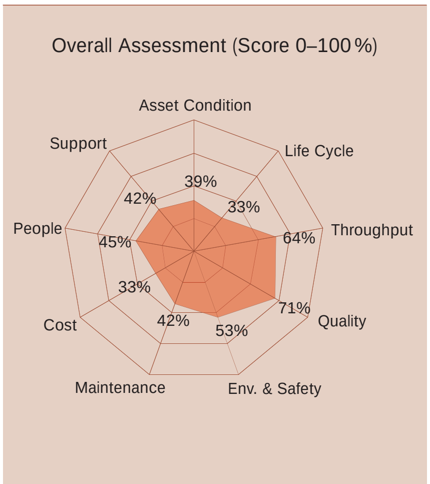
### Wastepaper recycling plant

Results from the I&C assessment of the paper recycling plant are presented in [5]. The assessment highlighted short falls related to the lifecycle of the control system and identified that the current control system would have been unable to cope with the planned expansion of capacity. The low cost score is also linked to the age of the control system, since more than 50 percent of maintenance time is spent on reactive maintenance. A preventive maintenance strategy should reduce this time and allow more time to be spent on improving the performance of the control system.

[4] Example of an OEE loss graph for a paper machine




[5] Result of the technical assessment of a recycled fibre plant for waste paper



Even though production was already at a high level, significant variations in the production rate were observed, resulting from different operator practices. By using common setpoint management and corresponding operational procedures, it should be possible to stabilize the production rate at its maximum.

**Without computer support it would be difficult to conduct a broad assessment of a plant's performance within such a short time with a staff of only one or two people.**

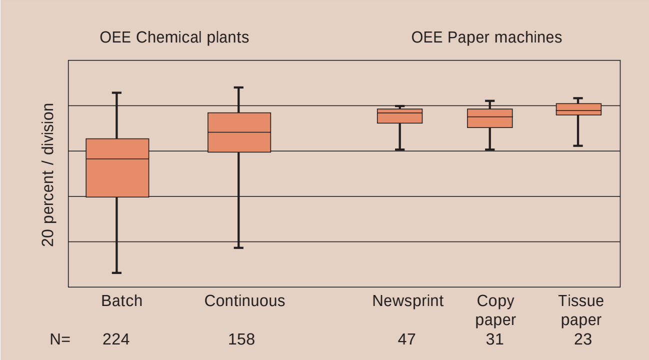
### Paper manufacturing

In the case of the paper machine, the PAS assessment provided the results shown in 7. After extensive modernization of the control system, the customer consistently obtained good results for the KPIs Asset Condition and Support. Low cost performance was highlighted by the assessment and attributed to suboptimally coordinated support from the plant's own maintenance and engineering departments, as well as from suppliers and other third parties. A better clarification of responsibilities was suggested to help improve efficiency and lower costs.

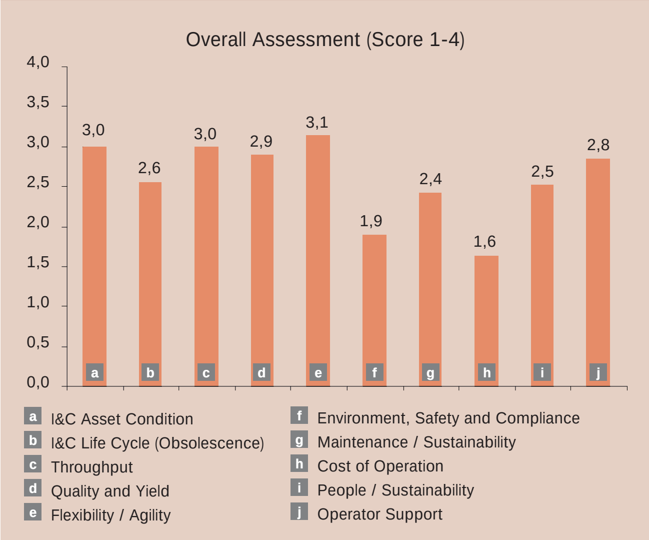
### Chemical processing

After assessing and benchmarking the continuously operated chemical plant yield, energy efficiency, and capacity were identified as major areas for improvement. Measures to improve plant operations were implemented after conducting a detailed engineering study. More precisely, measures to reduce yield losses by 10 percent were identified. No investments were required to realize this potential, just some adjustments to the control system and operational procedures. Energy savings of up to 15 percent could be made by modifying the plant's operation. The customer remarked that relevant issues were rapidly identified using this systematic approach and more objective results were obtained using external assessors.

6 OEE distribution of a sample of chemical plants (left; error bars indicate minimum and maximum; lower and top box boundaries indicate first quartile, median, and third quartile) and of a sample of paper machines (right; error bars indicate minimum and maximum; lower and top box boundaries indicate median, top 25 percent, and top 10 percent)




7 Result of the technical assessment of a paper machine




### Summary and outlook

The method and computer-aided tool described in this article can be used for the rapid assessment and benchmarking of automation systems, their performance and related working procedures. Potential for improvement can be identified and its economic impact estimated. This new method has helped customers to identify the most relevant issues in several pilot studies.

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Footnote

[1] A similar version of this article was published in German in 2006 [1].

References

[1] Kroll, A., and F. Simon. 2006. Assessment and opportunity screening regarding automation systems and working practices in the process industries (in German). Automatisierungstechnische Praxis, Vol 48, No. 8, 42–49

[2] Ahmad, M., and R. Benson. 1999. Benchmarking in the process industries. Rugby: IChemE. ISBN 0 85295 411 5

# Power semiconductors

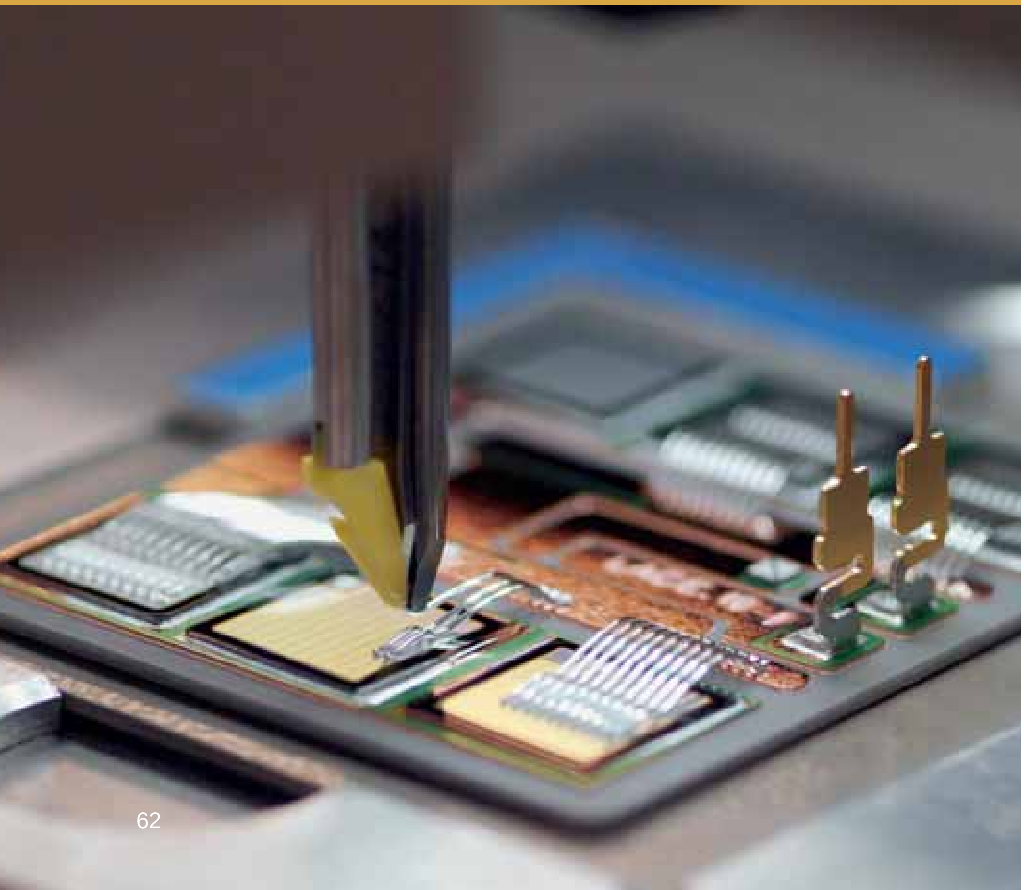
## Part two: Housing technology and future developments

Stefan Linder

Power semiconductors have, over recent decades, become ubiquitous in a broad range of applications. This was a consequence of the continuous and rapid development of power semiconductor technology, resulting in very powerful, effective, and easy to use devices. In the first part of this article, published in the previous edition of ABB Review[1], aspects of chip design and optimization were discussed, as were considerations of the application of different classes of devices, notably of IGBTs and IGCTs.

The continuous optimization of silicon has brought performances closer and closer to the physical and technological limits. The result is that, short of radically new breakthroughs, the potential for further improvement in this aspect of the design is diminishing. Semiconductor device housings, however, still have considerable potential for leveraging performance. This article therefore looks further into this aspect.

Today, virtually all commercial power semiconductors are entirely silicon-based. Looking into the future, this article further discusses the potential of so-called “wide-bandgap” materials, such as silicon carbide, gallium nitride, and diamond.



Whereas, until about a decade ago, power semiconductor housings were not much more than containers for the devices, they are now more and more becoming the limiting element in power electronic systems. The attention of developers is, therefore, increasingly focusing on aspects of housing design to tackle its limitations.

### Housing forms

Two conceptually different housing forms have become established in the high-power range: the insulated housing and the pressure-contact module 1. The main difference between them is that the electrical circuit in the insulated module is galvanically isolated from the heat sink by a ceramic insulator, whereas in the pressure-contact design, the current flows vertically through the entire module, ie, also through the heat sink.

Both housing forms are fundamentally suitable for IGBTs and IGCTs. In practice, however, IGCTs are currently only offered in pressure-contact housings, whereas IGBTs are manufactured in both variants. The insulated housing currently dominates in systems with low output powers (mostly below one MW), as the circuit can be implemented with a lower mechanical outlay (and hence at lower cost). The pressure-contact housing, on the other hand, is preferred for several reasons for output powers greater than approximately 10 MW. The two most important of these are discussed here:

Footnote

[1] Stefan Linder, Power semiconductors – Part one: Basics and applications, ABB Review 4/2006, pp 34–39.

- In systems with very high power outputs, semiconductors must be connected in parallel and/or in series. For the latter, pressure-contact housings present a considerable advantage, as the modules can be arranged in a stack, only separated by heat-sinks. One example of this is in HVDC (High voltage DC) power transmission installations, in which up to 200 modules are connected in series.
- A pressure-contact housing must be used if the application requires a guaranteed uninterruptible current flow (eg, a current-source inverter, but also all systems that must respond to a semiconductor or control fault by discharging the DC link energy by means of turning on all semiconductors). In a pressure-contact housing, the metallic pole pieces fuse if a semiconductor fails, thereby ensuring a low-impedance current path. In the insulated housing, on the other hand, the current flows through bonding wires, which evaporate upon a high current pulse during a fault, hence leaving an open circuit.

### Requirements for housing technology

The challenge in creating a housing design consists of two main factors:

- Modern power semiconductors are operated at a continuous power dissipation of 100–200 W/cm² of silicon. This power density is (per surface area) approximately one magnitude greater than a kitchen stove hotplate operated at maximum power. This poses extreme demands on the housing technology and the materials used.
- The coefficient of thermal expansion (CTE) of silicon is approximately five to ten times smaller than that of most metals (Cu, Al) suitable for electrical and thermal coupling. This means that critical components in the housing (bonding wire contacts, solder joints) are subject to considerable thermomechanical stress during load changes. This considerably limits their service life.

As a result of these requirements, there is no alternative to using expensive and highly sophisticated materials.

### Potential for improvements in the housing technology

#### Increased junction temperatures

The useful output power $P_{useful}$ of power semiconductor devices is scaled in accordance with the law:

$$P_{useful} \propto \frac{T_{j,max} - T_{ambient}}{R_{th}} \qquad (1)$$

$T_{j,max}$ is the maximum junction temperature, $T_{ambient}$ is the temperature of the heat sink (the ambient), and $R_{th}$ is the thermal resistance between the semiconductor junction and the ambient.

> Increasing the maximum junction temperature would enable the inverter to be operated at a higher switching frequency, resulting in reduced harmonics and so permitting filters to be smaller in size.

It is immediately apparent from this formula that the increase in the maximum junction temperature of high-voltage devices (above 1700 V) from 125 °C (today's standard) to 150 °C, results in an increase in performance of 25 to 30 percent (assuming an ambient temperature of approximately 20–40 °C). An alternative to using this performance increase for achieving a higher output power, is to "invest" the better cooling capability in larger losses at a given power. The latter would enable the inverter to be operated at a higher switching frequency, resulting in reduced harmonics and so permitting filters to be smaller in size.

In practice, a series of important preconditions must complied be with, to permit this potential to be fully utilized:

#### 1) Properties of silicon

- The power semiconductors must still be able to safely turn off the larger rated current at the higher junction temperature.
- In voltage inverters, the freewheeling diodes must be able to safely withstand the increased surge current in case of a fault.
- IGBT devices must still have an adequate short-circuit withstand time.
- The silicon components must exhibit stable behavior at 150 °C, ie, they may not permit any temperature-induced accelerating current redistribution.

#### 2) Properties of the housing and interconnection technology

- The interconnection technology must have an adequate thermomechanical fatigue resistance caused by alternating loads.
- The materials used must tolerate the temperatures that arise.

The surge capability of freewheeling diodes usually represents a major obstacle in optimizing a semiconductor's application – in fact, it is often the limiting element, already at 125 °C. An increase in output power, however, usually goes along with an increased demand in terms of surge current. This requires larger diodes, which reduces the remaining space for switching devices (IGBT or IGCT), and generally also results in an increase in turn-on losses. Hence, without innovative approaches, the latitude for an increase in performance through an increase in the semiconductor junction temperature appears restricted. The potential is definitely significantly lower than the purely thermal consideration of the formula (1) suggests.

The thermomechanical fatigue resistance to alternating loads is the primary limiting factor in the interconnection technology. 2 shows the capability of modern insulated high-power modules in the case of a maximum junction temperature of 125 °C, and the approximate corresponding curve for the same module construction if $T_{j,max}$ is increased to 150 °C. The figure also shows the curve that would be required to provide the system with the life expectancy at 150 °C as it has at 125 °C. It can be seen that demands increase markedly at a higher maximum junction temperature, especially at large temperature excursions. This is because significant changes in the load conditions (eg, full load/zero load cycles) cause a higher temperature excursion (by up to additional 25 °C). The demands do not increase

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to such a great extent at a small ΔT, since the temperature of the junction is influenced to a lower degree by small fluctuations in power output. For example, if the power output drops from 100 to 90 percent at an ambient temperature of 30 °C, the junction temperature decreases by 9.5 °C at $T_{j,max}$ = 125 °C and by 12 °C at $T_{j,max}$ = 150 °C.

Considering the fact that the load cycling capability of modern products only barely meets the requirements in many applications (particularly in traction), it can be inferred that an increase in the capability of the modules by at least a factor of five is required to increase the junction temperature to 150°C. This may only be possible through the development of new technologies. In particular, large-area solder joints will probably have to be replaced by improved connection technologies. Perhaps the most promising candidate is the so-called low-temperature bonding (LTB) technique, which connects two parts by a spongy silver flake-based sinter layer. In addition to increased resilience to load cycling, low-temperature bonds also exhibit lower thermal resistances.

### Reduction in thermal resistance

As an alternative to increasing the maximum junction temperature, an increase in the output power can also be achieved through a decrease in the thermal resistance $R_{th}$ (see formula 1). The typical distribution of the $R_{th}$ in an assembly with an insulated high-power IGBT module containing a total IGBT surface area of 45 cm² is approximately as follows:

| | |
|---|---|
| IGBT junction to the AlSiC (Aluminum Silicon Carbide) base plate | 7 K/kW |
| AlSiC base plate to the heat sink (dry contact) | 6 K/kW |
| Heat sink to the ambient | 10–35 K/kW* |

* This value is strongly dependent on the cooling method (low for liquid cooling, higher for forced air convection cooling)

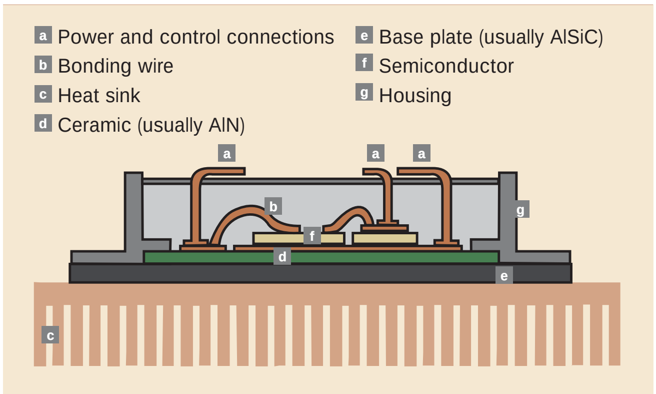
What stands out is that the dry contact of the module to the heat sink has approximately the same thermal resistance as the module itself, and that 40 to 70 percent of the entire $R_{th}$ is located between the heat sink and the ambient. Hence, addressing the module-external $R_{th}$ promises to yield greater returns than exclusively concentrating on that within the module. The motivation to work on the module-external $R_{th}$ is further fueled by the large performance margins of modern devices (as explained in ABB Review 4/2006), and by the fact that new materials are beginning to emerge that are capable of reducing the internal thermal resistance of the modules by 30 to 50 percent. Such materials include advanced MMCs (Metal-Matrix Composites) which have both a favorable CTE adaptation and an extremely high thermal conductivity. Diamond MMCs, whose thermal conductivities of 400-700 W/mK even surpass copper, are an example of this. On account of its high CTE difference from silicon, copper is only used in combination with other materials that have an adapted CTE (eg, molybdenum 1i).

**The surge capability of freewheeling diodes usually represents a major obstacle in optimizing a semiconductor's application – in fact, it is often the limiting element, already at 125 °C. An increase in output power, however, usually goes along with an increased demand in terms of surge current.**

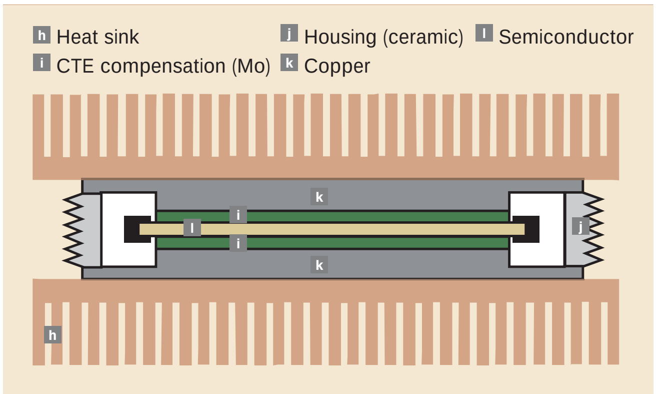
In addition to improvements in the heat sink, the dry (non bonded) contact to the module deserves special attention. Its thermal resistance is not only high, but also notoriously susceptible to variations, since a homo-

1 Common housing forms for high-power semiconductors:
An insulated module (left) and a pressure-contact module (right, a typical IGCT is shown here).

In insulated **housing modules**, the semiconductor f is galvanically isolated from the heat sink c. Electrical contacts within the module are provided by bonding wires. In case of a device failure, these wires tend to evaporate and the module ceases to conduct.




In **pressure contact** modules, the load current enters through one surface k and leaves through the opposing surface. Low electrical and thermal resitances of the contacts are assured through high mechanical pressure on those surfaces. In the event of a failure, the metallic pole pieces i fuse and current can continue to flow through the module.



geneous contact pressure and a good contact of the surfaces are difficult to ensure. The use of thermal greases and silicone oils only slightly alleviates the problems, since the thermal conductivity of these substances is at least a factor 100 lower than those of the metals of the base plate of the module and the heat sink. A very promising approach to the solution of this problem lies in the use of special metallic interlayers with high thermal conductivity, whose properties are designed so that they turn very soft or even fluid under operating conditions. Hence, they form a connection between the heat sink and the module that exhibits an $R_{th}$ similar that of a bonded joint. As an alternative to this, it is also conceivable that modules with an integrated heat sink will experience a revival, since the dry contact has been completely eliminated in this concept. Such products have not been able to establish themselves on a wider market so far, for reasons of cost and complexity.

## New semiconductor generations

### Silicon devices

Especially in the 90s, a large number of novel component ideas were examined, of which the MCT (MOS-Controlled Thyristor), the FCTh (Field-Controlled Thyristor) and the EST (Emitter-Switched Thyristor) are the best known. The common objective of these device concepts consisted in combining thyristor-like properties[2)] with lower driver power. Since all these components had conceptual deficiencies and because the plasma distribution in modern IGBTs has already closely approached the thyristor ideal, innovation with regard to new types of structures has markedly decreased in the meantime. Today, the probability of the IGBT and the IGCT being replaced by a fundamentally different silicon component seems remoter than ever.

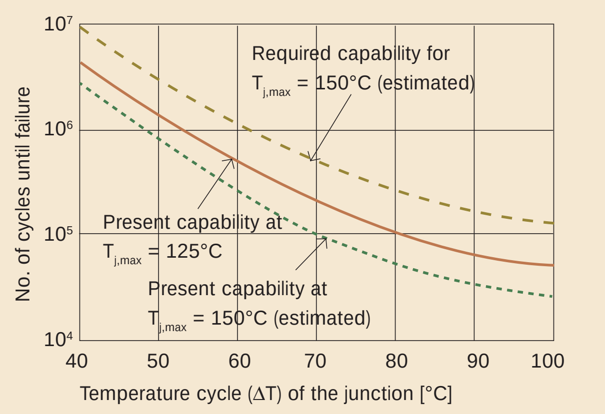
### “Wide bandgap“ materials

Components based on so-called “wide bandgap“ semiconductor materials represent an alternative direction of development. The advantage of these materials, the most well-known of which are silicon carbide (SiC), gallium nitride (GaN) and diamond (C), consists in their distinctly higher breakdown field strength in comparison to silicon. This enables significantly lower component thicknesses and higher dopings of the mid-section[3)] than in silicon, which, for reasons discussed in part one[4)], leads to considerably lower losses in the semiconductor.

A fundamental problem of SiC components with conductivity modulation is attributable to the fact that SiC pn-junctions only begin to conduct at approx. 2.8 V (in contrast to silicon, which only requires a voltage of approx. 0.7 V).

Only SiC can presently be considered a serious candidate in the high-power range. SiC is so far the only material that enables vertical components, ie, components, in which the current flows vertically through the semiconductor body and not along the surface. Only such vertical construction permits an adequately large cross-section to be provided for the required currents, while maintaining an acceptable component size.

**2** Fatigue life expectancy as a function of thermal excursions of modern insulated high-power IGBT modules with AlSiC base plates (eg, ABB HiPak or Infineon IHM)




### Preferred SiC component concepts

Similarly to silicon, SiC permits the manufacture of both unipolar and conductivity-modulated (“bipolar“) semiconductors. On account of the larger permitted drift zone doping, however, the economic use of unipolar SiC components is viable up to significantly higher blocking voltages than with silicon, specifically up to about 2–4 kV. However, bipolar SiC components are clearly in the focus of interest for use in the high-voltage and high-power range.

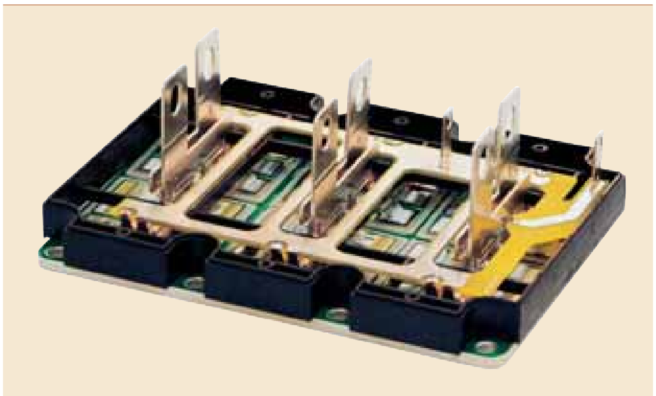
- In the case of unipolar components, Schottky diodes with nominal currents of up to 20 A and voltages up to 1200 V are already commercially available today. They are mainly used in switching power supplies and in solar cell inverters. Furthermore, unipolar SiC switches (MOSFETs and JFETs) have already been successfully manufactured, albeit only on a laboratory scale. A serious problem consists in the fact that SiC MOSFETs and SiC JFETs with attractive electrical characteristics have so far always been naturally conductive („normally-on“). Components with such characteristics have never been accepted by the market, even so the associated challenges appear to be technically solvable.
- In addition to diodes, bipolar components such as IGBTs, bipolar transistors (BJT) and thyristors for voltages up to 10 kV have already been successfully manufactured. In the case of the BJT, it should be noted that although it is a bipolar component, usually no conductivity modulation occurs in the conductive state (unless it is operated at a very low gain). The BJT must, therefore, be classified as a unipolar component on account of its loss characteristics.

A fundamental problem of SiC components with conductivity modulation is attributable to the fact that SiC pn-junctions only begin to conduct at approx. 2.8 V (in contrast to silicon, which only requires a voltage of approx. 0.7 V). Since all

## Ease of use

Assembly of a HiPak power semiconductor module


Inside a HiPak module (see also page 64, 1 left)



conductivity-modulated components have at least one pn-junction in the current path, they have high conduction losses. This makes them unattractive below a breakdown voltage of approx. 4–6 kV. In addition, the current onset voltage ("built-in voltage") of SiC pn-junctions has a very negative temperature coefficient. This can lead to a risk of inhomogenous current distribution in large components.

### Material quality of SiC

SiC still remains a material which is very difficult to produce in a quality comparable to that of silicon. The frequently discussed "micropipes" are only one of a series of harmful crystal defects, some of which can have a negative effect on the device's long-term stability, especially in the case of bipolar components. The industrial production of large-area SiC components is, therefore, not yet possible. Another negative point lies in the fact that the incentive to improve the quality of SiC is rather low. This is because most SiC is not used for the production of power semiconductors, but as a carrier material for the manufacture of LEDs (light-emitting diodes). A different type of SiC is used for LEDs (6H instead of 4H), and a much lower material quality is adequate for economic production, on account of the minimal size of the LED.

### SiC housing technology

It is undisputed that SiC components will, even in the long term, remain considerably more expensive than silicon components of the same size. The prospect of commercial success in the high-power range is based on the fact that the components are able to operate at a significantly higher current density than silicon components due to their lower losses, and on the higher permitted junction temperature (in excess of 400 °C). Unfortunately, there are two serious obstacles standing in the way of this objective:

- For the reasons mentioned in the subsection "Increased junction temperatures", it is difficult to establish a housing technology which permits significantly higher junction temperatures than is usual in silicon. It can therefore be assumed that the losses per unit are of large-area SiC devices must remain within the same limits like those of silicon components, provided that reliability requirements remain unchanged.
- In addition, there is the problem that SiC devices have shorter switching times (ie, higher di/dt) than silicon. Because of this, the permitted stray inductances in housings are lower than for silicon components. However, the fact that stray inductances are mainly determined by insulation clearances and conductor cross-sections makes it difficult to achieve the required values in housings for high output powers.

**Only SiC can presently be considered a serious candidate in the high-power range.**

Unfortunately, the combination of SiC material quality problems, high costs, and technological difficulties both in the components and in the housing technology, reduces the prospects of SiC breakthrough in the high-power range within the foreseeable future.

### Summary

IGBTs and IGCTs have established themselves as the two most successful semiconductor switches in the highest power range in recent years. Both concepts are developing in parallel, and it can be observed that the development objectives are increasingly converging. At the present stage, both components can be considered mature, ie, quantum leaps seem unlikely, and future progress is likely to take the form of evolution rather than revolution. However, this does not apply to housing and interconnection technologies, which may permit to exploit the so far unused potential of silicon. The motivation to innovate in this area is high, as the large scale introduction of "wide bandgap" materials to the high-power range is still a long way ahead. At present, SiC appears to be the only one of these materials to have a realistic chance.

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Footnotes

[2] See also the sub-section "Optimization of forward-power losses and turn-off losses by adjustment of the plasma distribution" on page 36 of part one of this article (ABB Review 4/2006).

[3] The so-called drift zone – see figure 4 on page 37 of part one of this article.

[4] See "Design objectives of the IGBT and the IGCT" on page 35 of part one of this article.


# Plainly speaking

## Natural language interaction in industrial automation

Juan S. Jaliff, Magnus Larsson, Morgan Johansson,
Boris Katz, Gary Borchardt

When seeking information in a public library, readers can choose between different ways of finding the right shelf. One way involves consulting the library's classification index. This can, for trickier enquiries, be a time consuming and confusing activity that misses vital information from related categories. When unsure, it is preferable to ask the librarian. The librarian understands a question formulated in plain language and can point to the desired shelf immediately.

Similarly, when accessing plant information from the control room, an operator may have to drill down through several layers of sub-menus to access fragments of information that only make sense when combined with further fragments from elsewhere in the system. This may take a well-trained operator in a frequently recurring situation just a couple of mouse clicks – but is much more challenging for rarer scenarios. If only the computer, like the librarian, could understand natural language! This is exactly what a joint research project of ABB and MIT is out to achieve.

How much training is required to access key process information at an industrial plant? How can knowledge and experience be easily exchanged between the skilled staff members that need to work with it? Industrial facilities continually face such questions, as more specialized personnel are needed to operate and maintain production lines at ever more competitive output levels. What if the ever increasing information processing and storage capacity could be better utilized by making its data accessible more easily? MIT and ABB research labs have jointly demonstrated a technology that will enable users of the future to query an automation system in plain English. This tool can handle large amounts of process and plant information, building upon the flexibility of modern ABB automation system software. Challenges ahead lie in automatic annotation of information and extraction of knowledge from query sessions.

### Background

A system for industrial automation is typically characterized by several thousand I/O signals, controlling several hundred real-life objects on the plant floor, eg., valves, tanks, motors, reactors and the like. Operators and other users interact with the system by way of a GUI (graphical user interface). A display system manages a hierarchy of up to several hundred screens representing the various sections of the process and/or groups of process objects.

Retrieval of process information can nevertheless be painstaking – object information is stored in multiple repositories following industry standards such as OPC for data access, history, alarms and events, etc. Naming conventions for objects and their values or properties vary from plant to plant. Furthermore, it is often necessary to additionally access maintenance and condition-monitoring data in order to make better operational decisions.

### Human in the loop

The central problem lies in finding a way to empower the user to come to grips with this over-abundance of information, while keeping him in the loop. Is there a mode of communication that can facilitate interaction while keeping decisions in human hands? One response offering multiple advantages is the user's natural language. It requires no training and encourages interaction. A system that can remember a user's question and answer sessions can later recall them in similar situations, building up a personal knowledge base. This can be of great value for troubleshooting under stress, particularly in seldomly recurring scenarios. Moreover, the user can choose to share this knowledge with other operators, shifts and even other plants. In other words, it is useful for building an informal knowledge management system. Such a system is especially powerful when senior expert staff contribute.

### Related research

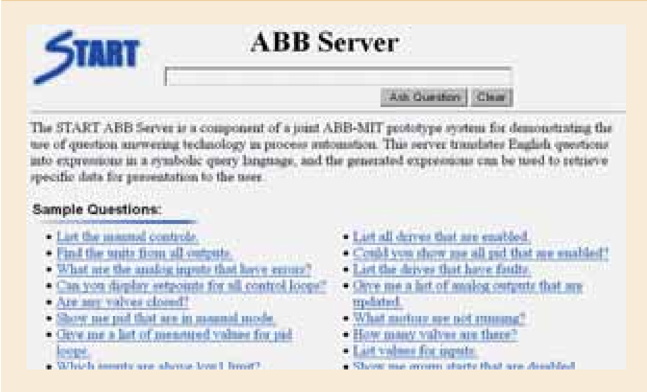
The advantages of using natural language for queries are apparent in systems which can search information on the web.

The START system [1] is a good example. It answers natural language questions by presenting components of text and multi-media information drawn from a set of information resources hosted locally or on the Internet. These resources contain structured, semi-structured and unstructured information. START targets high precision in its question answering. Its ability to respond to questions derives from its use of natural language annotations as a mechanism by which questions are matched to candidate's answers [2]. START's potential for use in industrial automation was identified in discussions between researchers at MIT's CSAIL lab and ABB visiting scientists.

### Innovative approach for industrial automation

ABB researchers identified the main types of information requests and validated them through field interviews at customer plants. XML schemas with classes of process objects were developed in close cooperation with MIT, whose researchers customized the START server to handle these requests 1. Current development is based on queries in English, but future developments could see other languages being addressed.

1 Web interface to the START question translation

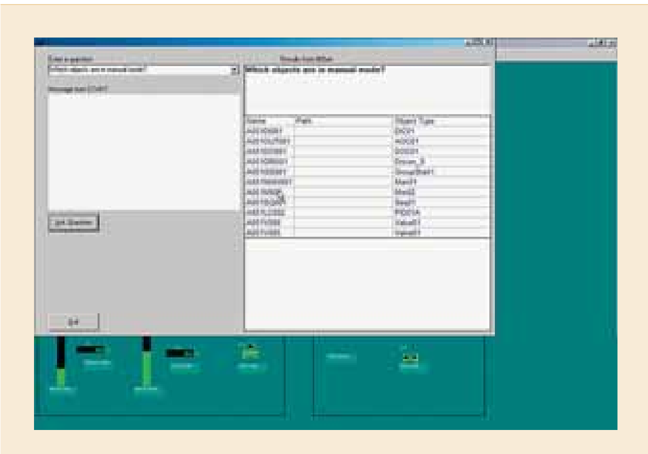



The project initially focused on four types of requests. These were requests to (1) display all members of a class (eg, „Show all inputs") (2) display those members of a class that meet a specified condition (eg, „Get all drives that are interlocked") (3) display all members of a class, accompanied by related items of another class (eg, „Get position unit for all control valves") (4) display those members of a class for which a related item meets a specified condition (eg, „Which digital inputs have unacknowledged alarms?")

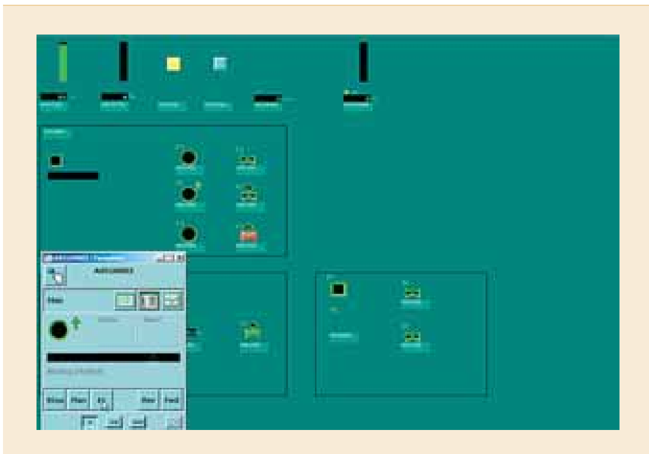
The START system answers natural language questions by presenting components of text and multi-media information drawn from a set of information resources hosted locally or on the Internet.

MIT's START system translates English requests into standardized symbolic expressions that can be easily converted into database requests. As an example, the English request, "What manual stations have active interlocks?" is translated by START into the following expression:

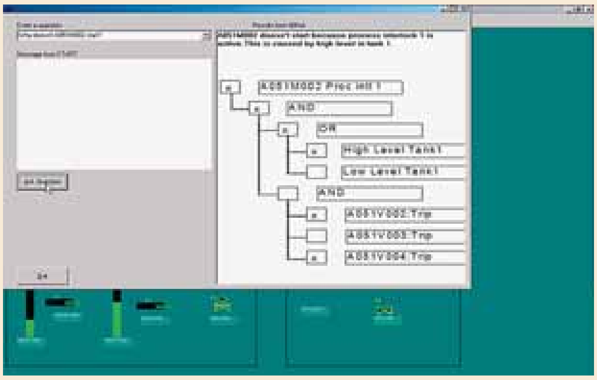
2 When starting a process section, the operator wants to check the control mode of the included objects before enabling the automatic start-up sequence



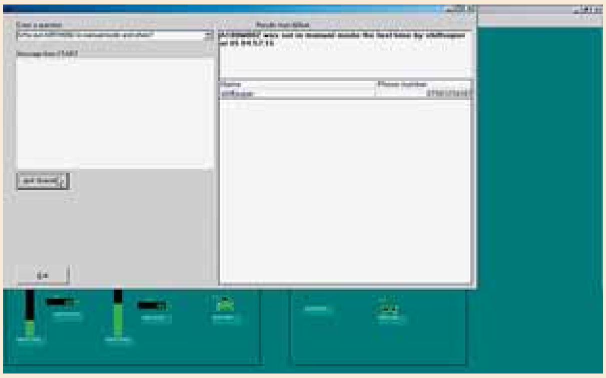
3 The motor found to be in manual by the plain-language query is now put into automatic mode through a faceplate



4 The start-up sequence was aborted. It takes only a simple question to make the system reveal what went wrong




5 The problem is corrected but the operator wants to find out why motor A051M002 was in manual to begin with. With a phone call he knows.



```
<?a, "is a", "manual station">
<?b, "is related to", ?a>
<?b, "is a", "interlock">
<?b, "is", "active">
```

The standardization performed by START allows the human user to enter requests in many variants. For example, START will translate each of the following requests into the symbolic expression listed above:

- List the active interlocks for manual stations.
- What are the interlocks that are active from each manual station?
- What are all manual controls with active interlocks?
- Let me see all manual controls with interlocks that are active.
- Find the interlocks that are active for manual stations.
- Get me a list of active interlocks from all manual stations.

At ABB, the company's 800xA system was used as a test bed for these ideas. Its flexible software architecture enabled a relatively straightforward implementation of query responses. A simple dialogue interface was also added to existing GUI facilities 2 3. This demonstration system featured live online connectivity with the customized START server at MIT.

## Further challenges

Users have shown a keen technical interest in the demonstration system and have provided much feedback. Estimated benefits in use depend on the type of industry and the target user group. Casual users, eg., maintenance engineers, and operators of flexible processes could benefit the most from being able to pose open queries in plain written language. At the other end of the spectrum, operators of highly standardized plants receiving periodic training probably benefit the least because the facilities for graphically navigating 800xA data structures from the GUI are adequate.

**The START system can be of great value for troubleshooting under stress, particularly in seldomly recurring scenarios.**

The foremost challenge consists in finding a way to produce annotations semi-automatically, with minimal, data-driven manual guidance. In particular, in order to process requests such as those illustrated in 4 and 5, high-level annotation techniques must be developed that allow application developers to specify entire classes of explanation procedures with a few descriptive annotations.

Depending on the type of decisions that must be based on system responses, the annotations and underlying explanation procedures may need to provide responses that are 100 percent reliable and complete if the system is to have any value at all. In current automation systems, this is achieved by manual configuration of a limited number of queries. Is there a use and value for queries that return, eg, 90 percent complete answers, in terms of correct interpretation and processing? If so, this project has already found an application. If not, the challenge remains.

Secondary challenges are the adaptation to languages other than English, and of modes such as responding to spoken language rather than writing. None of these challenges are trivial, but technologies are commercially available that can be added to this demonstrator, enabling it to perform such tasks.

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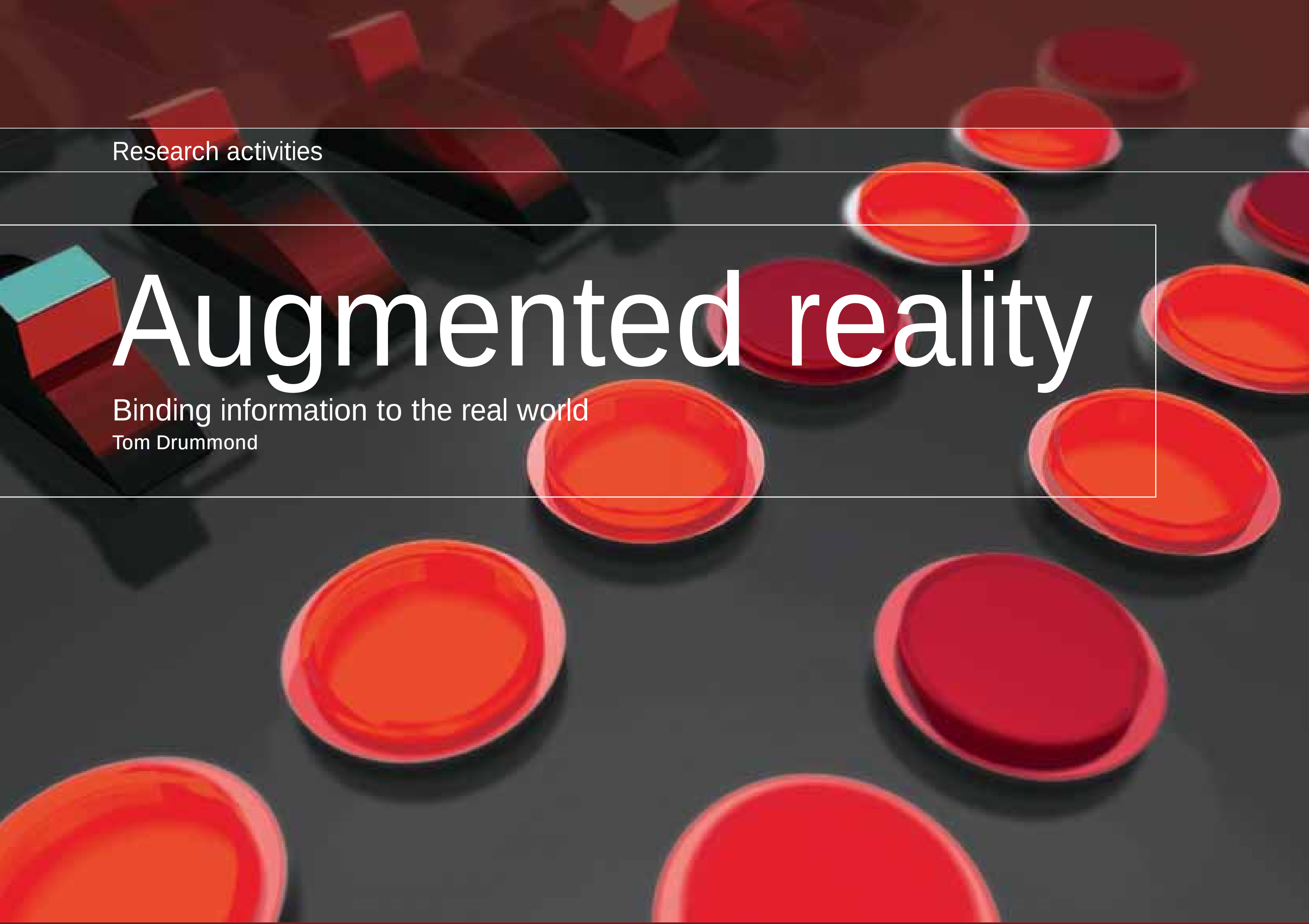
[2] Boris Katz, Gary Borchardt, Sue Felshin, Natural Language Annotations for Question Answering. Proceedings of the 19th International FLAIRS Conference (FLAIRS 2006), May, 2006.



# Augmented reality

## Binding information to the real world

Tom Drummond

Adjusting the volume of a television set might seem a fairly intuitive task. But when there are several remote controls to choose from, finding the right one may be a trial and error process.

In industry, similar situations occur. Even well-trained and experienced operators may sometimes have difficulty knowing which switch corresponds to which function. In a rarely occurring but critical situation, valuable time is lost as the operator struggles to find the right switch.

In contrast to using the wrong remote control in the living room, which causes no more damage than wasted time and embarrassment, errors in an industrial environment can have severe and costly consequences. Is there a better way of providing relevant information?

Most modern engineering solutions contain a software component. There are computers in everything from televisions, cars and kitchen appliances, to large-scale industrial plant systems. A modern credit card has an embedded microprocessor and enough software to run a file system, authenticate the owner's presence and create digital signatures for financial transactions. This ubiquity of computing in engineering solutions has resulted in an increase in software complexity.

Just as engineering involves the construction of mathematical models of a problem and its environment, so software engineering requires the creation of software models; a credit card has a software representation of financial transactions (who is paying whom how much?), the owner (name and billing address) and authentication (has the user authenticated and what is the procedure for doing so?).

This increase in complexity brings with it a number of problems that arise because the relationship between the software's model of the world and the real world (or the user's model of it) may not be obvious. One way in which this manifests itself occurs when software has an internal state that may not be visible or obvious to the user. One example is a software controlled indicator in a car. Instead of the state being represented by the position of the indicator stalk (up = right, down = left, centre = off), such software-controlled systems see the stalk immediately return to its central position on release by the human. The record of the direction in which the stalk was pushed is stored only by the software. The same is true for how hard the stalk was pushed (soft = blink indicator lights only a few times while changing lanes and then cancel automatically, hard = blink lights until cancelled by pushing softly in the other direction). The problem is that the driver does not necessarily know which of these modes has been engaged as both result in the same immediate behaviour (the indicator lights activate). If the driver incorrectly believes that the soft mode has been activated, the vehicle will continue to indicate beyond the time required. On the other hand, if the driver incorrectly believes the hard mode is engaged, the vehicle will indicate in the wrong direction when he or she attempts to cancel.

Another way that increased complexity causes problems can loosely be termed the *binding problem*.

### The binding problem

One classic example of this problem occurs in large rooms with many light switches. A user may wish to turn off a particular bank of lights, such as those near a projection screen, but is faced with a panel of many switches. How can the user know which switch operates which light? (the usual approach is to try them all in turn until the desired outcome is achieved). This problem arises because the *binding* between the switches and the lights is not obvious, and because such rooms are typically only used intermittently by a given individual, making the binding difficult to memorise.

The author's living room provides another typical example. On the table next to the sofa there is a small mountain formed of six remote controls. These control the TV, video, CD, networked music, cable and digital TV box. Visitors find it nearly impossible to figure out which remote controls which unit (some members of the household have difficulty too). Again, this is because the binding is not obvious. The situation could be improved somewhat with a universal remote control, but even then an operation such as muting the sound to take a telephone call requires identifying the correct device 1.

Anyone who has hiked in mountainous country knows that map reading is a real skill. It is possible to have a very clear view of both the local scenery and a map, but still to be lost as the binding between mountains as seen in the real world and those seen on the map is not always obvious.

> Even well-trained and experienced operators may sometimes have difficulty knowing which switch corresponds to which function. In a rarely occurring but critical situation, valuable time is lost as the operator struggles to find the right switch.

The design and operation of large plant control systems also introduces a binding problem. Such systems present the operators with control views of the plant, which are topological in nature. It is not uncommon for such views to collectively make reference to tens of thousands of tags, each of which corresponds to a component or location within the plant. Many of the alarms generated by the control system require that the control room operator interact with a plant operator by radio in order to make a visual verification concerning some component of the plant. This means that these two users must manually perform the binding between the very large database of tags and the real plant components to which they refer.

This human complexity has consequences in both training times and in speed of response to rare circumstances.

1 Which remote control goes with which device? This is a simple example of the binding problem


### Augmented Reality interfaces

One approach to solving the binding problem is to exploit new advances in Augmented Reality. These allow the software engineer to take the graphical user interface (GUI) capabilities of a conventional computer setup which are normally restricted to the computer screen, and make them available across the whole world.

This would be easy if the whole world had computerised input and graphical display output, however this is not the case and intermediary hardware is required. In the early days of AR, the most common way to achieve this was to exploit Head Mounted Displays (HMDs). Optical see-through head mounted displays contain a half silvered mirror which allow computer generated graphics to be merged with the user's view of the real world. This allows arbitrary graphical displays to be superimposed on real objects. Provided that the user's head can be tracked to sufficient precision, and the display can be rapidly updated in response, these graphics can be made to look as though they are stable in the real world and hence belong there rather than to the screen of the HMD.

One of the earliest examples of AR was implemented by the Boeing Company to assist in the production of wiring harnesses for aircraft. Such harnesses are normally constructed on peg-boards with each wire of the harness printed onto the peg-board, thus necessitating one peg-board per aircraft. In the AR setup, the worker wore a HMD which displayed the location of each wire onto a generic peg-board. Such a solution allows a significant saving in storage of peg-boards, but it admits many other benefits as well. It is now much easier to upgrade a design since the per-aircraft information is now stored only in the computer, rather than printed onto a board. Further, the dynamic capability of the HMD can be exploited so that the wires can be presented to the operator one or a few at a time.

Similarly, one can imagine that a hiker wearing a HMD could see the name of each mountain (or a grid reference) superimposed above the real view of their summit. Or the author could use a HMD in his living room, together with a pointing device displayed in the HMD to identify the item of entertainment hardware that he wishes to interact with by clicking on the real view of it . . .

. . . or are these examples rather a stretch of the imagination? In fact it is rather hard to picture a hiker choosing to obstruct his view of nature and the scenery by choosing to wear a bulky HMD. Similarly if somebody were to wear a HMD in the living room, family members would be likely to object to the impediment to social interactions.

There are also many other problems with HMDs as a means of delivery of Augmented Reality user interfaces. They can typically only augment a rather narrow field of view of the user and they still are rather expensive. For about $35,000 it is now possible to purchase a see-through HMD which augments 60 degrees of the user's field of view.

Such devices need to be calibrated specifically for each user so that real and virtual objects are seen to align. Finally, they inevitably have latency which means that as the user moves their head, the computer graphics lag behind the real motion, typically by at least 100ms. This is enough to cause serious motion sickness, restricting use to a few minutes at a time.

2 A handheld AR can simplify navigation

Factbox About the author

Dr Tom Drummond is a university senior lecturer in the machine intelligence laboratory of the department of engineering at Cambridge University and a Fellow of St Catharine's College. He received his PhD from Curtin University in Western Australia. His research interests include real-time computer vision, sensor fusion with an emphasis on applications to visually guided robotics and augmented reality user interface technologies.

## Research sponsored by ABB, is looking at ways of representing and matching models of the world against the live view coming from the video camera.

### Handheld AR

Such problems with HMDs have led researchers to consider other media for delivery of AR interfaces. The most popular alternative is handheld AR 2. This works by using a video camera attached to a handheld screen which acts as the viewfinder for the camera. AR is then implemented by trapping the video in-flight between the camera and the screen and editing it to insert virtual graphical objects and user interface components.

Handheld devices solve most of the problems with HMDs: they are cheap, nobody is concerned about small latencies, wide fields of view can be obtained by using a wide angle lens, they can be put away in a pocket and taken out as required. They also bring other benefits, for example by allowing the user interface designer to integrate conventional two-dimensional UI components into an application.

In the author's living room, anybody could pick up such a handheld device, point it at the entertainment hardware and see a live view of that hardware on the screen. Using a stylus, they could click on the image of the CD player and be presented with a conventional looking GUI for controlling it.

Similarly an operator equipped with this device in a plant could receive graphical navigation information superimposed over a live view of their environment to indicate which physical object corresponds to a particular tag. They could also click on the live view of an object to be presented with a topological view, or maintenance information, or sensor trends, or whatever else the application designer deems to be valuable to that operator. Further, such a device can be used to widen the communications channel between two operators beyond the single audio channel used at present to include geographically registered spatial information.

### What needs to be done?

Currently such devices are in their infancy and significant research effort is going into developing the tracking technologies that are needed to make them work. The most promising prototypes combine multiple technologies, for example using inertial sensors to supplement computer vision, or adding GPS or ultra wide band (UWB) localisation.

Such approaches have significantly improved the robustness and precision with which these systems operate. The author's research, sponsored by ABB, is looking at ways of representing and matching models of the world against the live view coming from the video camera so that AR can be provided robustly and reliably on demand in large scale environments, such as complex plant.

The benefits that can come from this are potentially substantial. Augmented Reality provides a way of solving the binding problem by making the real world act as an index into the database of computer system components. This in turn exploits the spatial capabilities of the human users which remains one of their great untapped strengths in conventional software systems.

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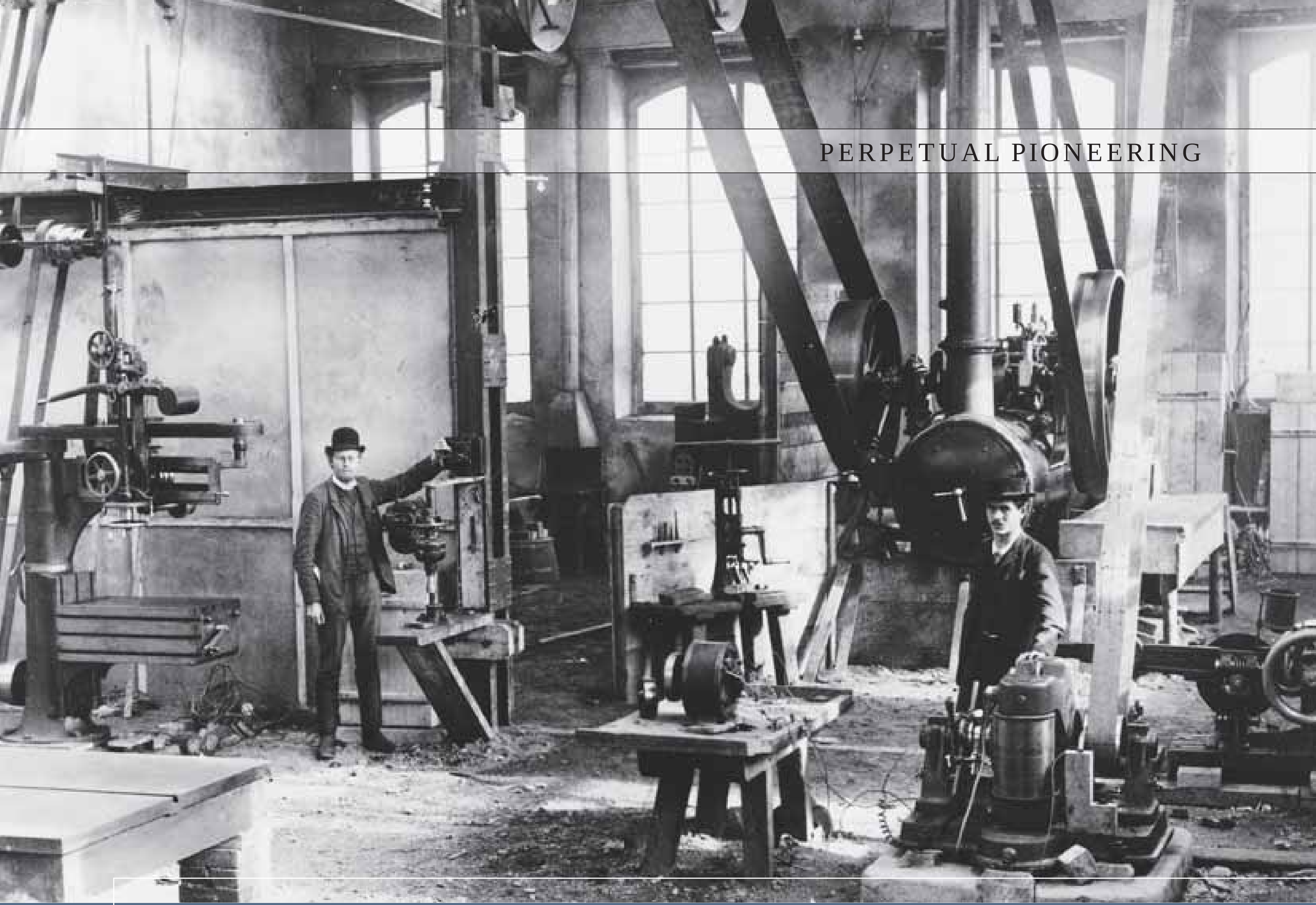


# Perpetual pioneering

Nils Leffler

ABB was formed a century after the foundation of its two parent companies. During these 100 years the electrification of nations changed the industrial world dramatically pioneered by a handful of companies founded in the late 19th century. However, the theoretical foundation of modern electrical technology was laid in the 18th century by scientists such as Franklin, Faraday, Ampere, Volta and Ohm. By 1830 telegraphy was introduced as a low voltage application of this energy form. Low voltage applications were also the basis for company formation during the following 50 years. The world saw lighting become a reality – initially outdoors only – using the arc lamp. With Thomas A Edison's electrical bulb (1878–79) indoor usage became possible. One of the few low voltage companies of the day that in 1880–1890 added high voltage products to its portfolio was Siemens & Halske. For most others the dynamo and lighting systems remained their core competence and branching out into the risky area of high voltage applications was not attractive. Instead, it was left to new company formations to embark on this high energy venture.

These companies were often founded by engineers and based on new patents or innovations. Companies in the USA and Germany quickly took the lead in this new industry.

Westinghouse Electric and Manufacturing Company was formed in 1884 to build electrical machines. It soon became the leading supplier of AC based transmission. The consolidation of several Edison companies combined with the merger with Thomson-Houston formed General Electric in 1892. In Germany, Siemens became successful in both the low and high voltage area. Edison's German operation became known as AEG from 1887 onwards. By pioneering work in the field of three phase alternating current it established itself as a major international contender.

# PERPETUAL PIONEERING

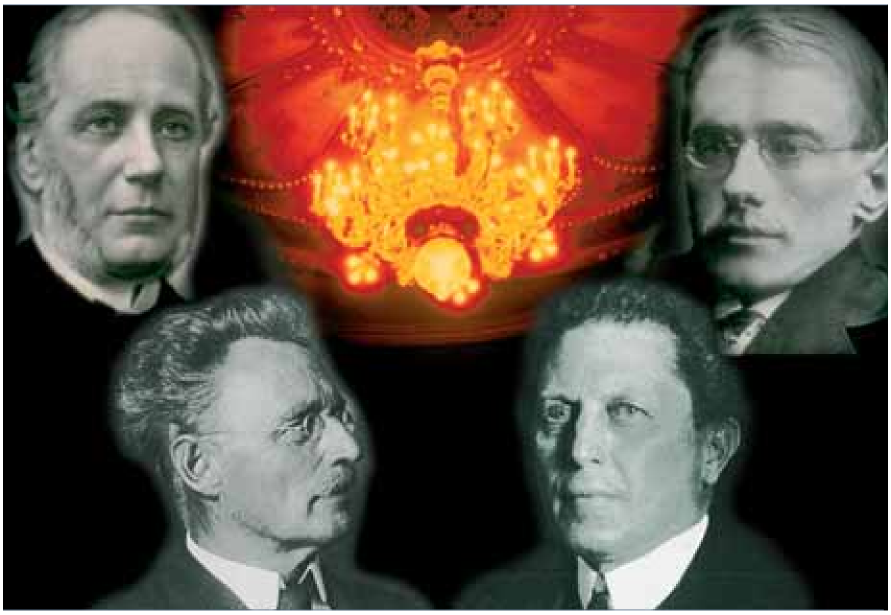
The reasons for the formation of larger entities lay not only in the internationalization of the business, but also in the scale of the investments required to construct and develop the electrical infrastructure for transmission and distribution of electricity to industry and homes. The ease with which electricity can be transformed into other energy forms such as heat, light and rotational and linear motions, combined with its ability to be transported over some distances with only minor losses, made it the driver of industrialization. Early electrical power applications were focused on transportation (street cars) and industrial applications in metallurgy and electro-chemical processes. Early distribution systems were based on direct current which permitted the source and the sink to be separated by a few kilometres at the most because of the rapidly increasing power losses over longer distances. Higher voltage levels reduced the losses but generators and electrical machines were not able to use these voltage levels. The technology promoted the development of small generating units close to the consumers, which soon proved impractical and inefficient.

Alternating current can be transmitted at high voltage levels with low losses over long distances. It could be transformed in both directions, hence it could be generated and consumed as low voltage while transmitted as high voltage. Towards the end of the 1880ies, no practically useful AC motor had seen the light and high voltage technology was considered dangerous and difficult. Roughly at the same time in the 1890ies several developers realised that three phase AC was the solution. The very first transmission line for three phase AC was the Lauffen-Frankfurt link in Germany – 175 km long, 30,000 volts – inaugurated August 24, 1891.

## ABB Review and its predecessor journals have covered electrification and its practical implementation in industrial applications since the early 20th century.

The flood gates were now opened for rapid expansion of electrically powered industrial applications. The technology allowed the use of centrally located generators, the connection of networks of different voltage levels, and the smooth transformation of electricity to suitable voltage levels. Engineers, meanwhile, had learned to calculate the performance and material usage of equipment more accurately and precisely. Electrical machines for many different applications were being constructed and safety was improved with breakers and switchgears.

Ludvig Fredlund (1830–1891) and Jonas Wenström (1855–1893), above
Charles E. Brown (1863–1924) and Walter Boveri (1865–1924), below



Switzerland with a small home market, established itself surprisingly early as a leading producer of high voltage equipment through the companies Oerlikon, 1882 and Brown Boveri (later BBC), 1891. Actually the two young engineers Charles E. Brown and Walter Boveri worked and met at Oerlikon, where they gained their early experience. They soon decided to establish their new company in Baden, where it rapidly grew into a substantial employer with a broad portfolio of electro-technical products and systems.

In Sweden, at this time, several international companies, among them AEG and Siemens, were involved in the electrification of the country. The only local company to make a larger impact was ASEA. This was formed in 1890 in Västeras, but its roots trace back to 1883, when its two parent companies were established. The inventor Jonas Wenström and the industrialist Ludvig Fredlund were the key figures in the formation of the new enterprise. Just as the portfolio of BBC, ASEA's included turbine generators and converters; electrical equipment for transmission and distribution such as transformers, breakers and switches; rotating electrical machines etc.

ABB Review and its predecessor journals have covered electrification and its practical implementation in industrial applications since the early 20th century. A look into the archives discovers a fascinating development of key products and solutions, which still today remain crucial for ABB's market success. This series will commence with a review of the history of the breaker, a key component in many electrical installations.

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# The circuit breaker

## A showcase of industrial product development

Fritz Pinnekamp

Over the last 100 years, electricity has become the world's most flexible and reliable form of power. Global demand is increasing and, in many countries, the supply of electricity is directly linked to gross domestic product.

The infrastructure that enables the safe distribution of electrical power is extremely reliable, but the development of ever larger networks and the introduction of new types of power generators are bringing new operational challenges. In this article, ABB Review traces the development of circuit breakers, an indispensable part of the electrical grid, highlighting the contributions made by ABB and its predecessor companies, ASEA and Brown Boveri – both pioneers in electrical power.

Circuit breakers are critical to the safe operation of an electrical grid. They are needed in electricity generators, where the full power of an entire power plant (gigawatts of electricity) must to be switched on and off, and on transmission lines in substations to direct the power flow at voltages in excess of 1500 kV. Circuit breakers are also critical components in distribution grids, where very high currents need to be managed at moderate voltage levels.

A circuit breaker, irrespective of its position in a grid has two tasks: it is responsible for the daily switching of lines during normal operation, and for the disconnection of the power supply in case of overload or short circuit. Several GVA of power can be tamed by a circuit breaker within fractions of a second.

Such is the importance of this single device that tens of billions of dollars have been spent on its development over the last 100 years.[1)]

### The challenge of a circuit breaker

Electrical current is transported from power plants to customers through electrically conducting, metal lines, most visible as overhead power lines. The current can be interrupted, simply by cutting the conducting power line: easy to do when there is no current flowing, but extremely difficult when the wire is live. As a live cable is being cut, the current is forced to flow through a progressively smaller cross-section of the wire. This concentration

Footnote

[1)] Circuit breaker systems in which free arcs do not form, ie, power semiconductor devices, perform extremely well at low power levels, but require further development for broader application in power circuit breakers.

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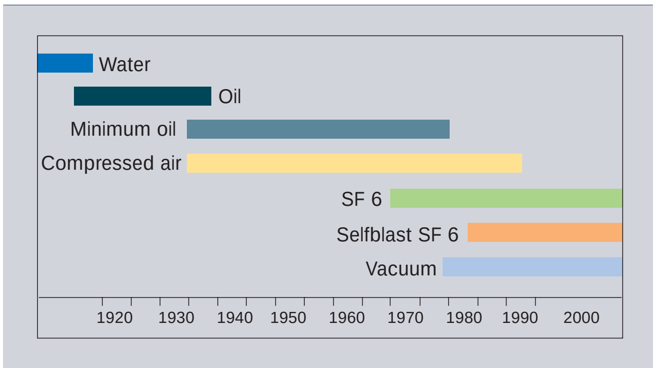
1 Major types of power ciruit breakers.




of the current leads to heating and eventual evaporation of the remaining wire. But even when the wire has been completely severed, current can continue to flow through an electrical arc that forms from ionized gases (plasma) between the opened contacts. The current can then be interrupted only by a circuit breaker capable of extinguishing this arc. While the speed with which circuit breakers must disconnect heavy metal contacts to effect their purpose has provoked a number of ingenious solutions, this article will concentrate on advances made in the considerable challenge of managing electrical arcs.

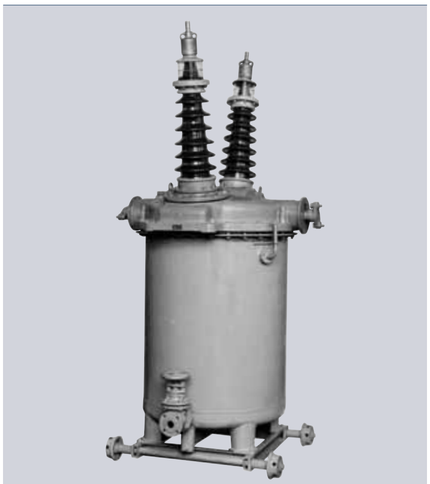
Electrical arcs have enormous energy: their temperature can exceed 50,000 °C and pressures up to 100 MPa can be contained within a volume of less than a liter. Over the years, circuit-breakers have incorporated a variety of different media to dissipate this energy, including water, oil, inert gases, and compressed air. The intense heat of the arc can be dispersed either by the application of a gas at high pressure, or by gas flow caused by the vaporization of the internal medium, which occurs as a result of arc formation.

## Several GVA of power can be tamed by a circuit breaker within fractions of a second.

The body of the circuit breaker also plays a critical role in the effectiveness of the device. It can be used to direct the flow of hot gases, and a range of different approaches have been taken to improve heat dissipation, including the use of semi-destructible materials. 1 gives an overview of the various types of circuit breakers used over the last 100 years by ASEA and Brown Boveri, and, more recently, ABB[1)].

Water- and oil breakers appeared early on in circuit-breaker development and worked at very low levels of current and voltage. 2 shows an example of an early oil-filled circuit breaker. The contacts in these breakers were embedded in a large tank, filled with the chosen medium. Under these conditions, arc formation led to ionization of the medium and the formation of hydrogen gas. When the current approached zero (eg, every 10ms in a 50-Hz alternating system), the high pressure of the vaporized medium compressed the gas-filled arc channel. This caused the medium between the opening contacts to lose most of its conductivity, thereby quenching the arc. Unfortunately, because of the large volumes of medium they required, these devices were rather unwieldy and, if an oil breaker failed, allowing pressure to build up, there was a significant risk of explosion and fire 2. Despite these risks, oil remained a popular medium and minimum oil breakers, based on these cumbersome early devices, were used until the 1980ies. The principle underlying the minimum oil breaker is shown in 3. Briefly, when current arcs in oil, the medium vaporizes and a bubble forms around the arc. This high-pressure gas, which is almost 80 percent hydrogen, inhibits ionization and moves through the channels surrounding the arc. It enhances convection in the oil, which helps to cool the arc residuals around zero current. This arc-induced-convection principle was later used in the "self-blast" breaker.

2 Outdoor single pole oil circuit breaker from 1923, 110 kV, 350 A.



Minimum oil breakers work best on high currents that provoke a sharp rise in pressure and strong convection. At lower currents, during normal operation, the self-blast effect cannot develop fully without the help of a moving piston to encourage convection 4.

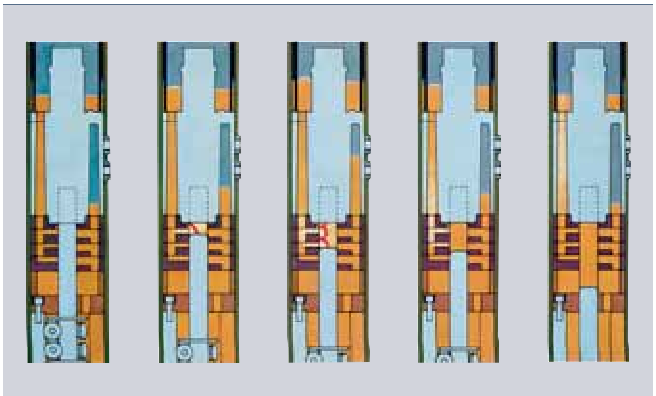
In these breakers, when the switch is opened, the current arcs and the pressure in the upper chamber rises significantly, causing the piston between the two chambers to move. At a certain point, an aperture in the piston passes the moving contact. This causes a strong axial flow of oil from the lower chamber, which cools the arc.

The obvious advantages of this approach led to a quick adoption of the minimum oil breaker and a phasing out of the conventional oil tank breaker, as the relative sales volumes around 1940 indicate 5.

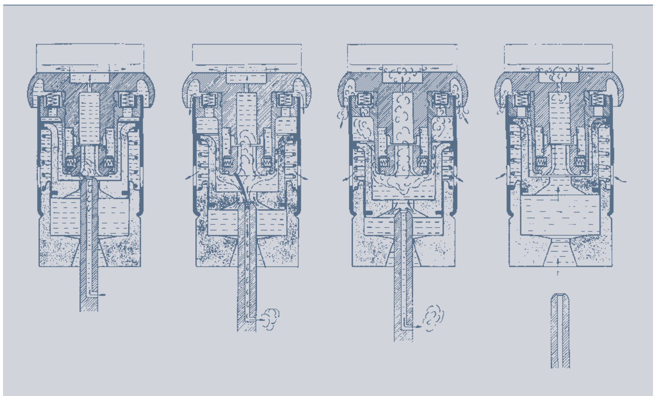
Oil is a good electrical insulator and, when the breaker is open, it can insulate grid voltage across the contacts. Comparable insulation can be achieved using air, but only if it is compressed to several MPa. The use of such high pressures in compressed-air breakers necessitated a new design of circuit breaker chamber, which was developed alongside that of the oil breakers during the early decades of electrification.

In compressed air breakers, the arc is cooled by convection caused by the large pressure differences between the inner parts of the breaker and the

3 Contact opening sequence of minimum oil breaker at short circuit current (1976).



4 The operation of the compression chamber upon breaking.



ambient air outside; a valve opens and compressed air rushes out of the chamber at high speed. A critical design component was ensuring that the arc was correctly positioned to benefit from the intense air flow. Various nozzle designs were tested and, finally, an axial flow, similar to that used in the compression chamber, was chosen.

There were several trade-offs between the compressed air breaker and the minimum oil breaker. The oil breaker, especially the self-blast type, had a simple design and could operate under low mechanical power. As a medium, however, oil was not easy to handle. It posed a fire risk and necessitated more maintenance. Compressed air breakers, on the other hand, required powerful compressors and were very noisy when operating. The high pressure could, however, be used to drive the movements of the contacts and compressed air-based systems were much cleaner and easier to maintain than their oil-based counterparts.

The market welcomed compressed air breakers and, between 1967 and 1971, sales grew by 20 percent every year. But the development of two breaker principles in parallel polarized opinion, even within the producing companies, and competition between the two camps continued with almost religious zeal. In 1955, some engineers claimed that, “The air-blast breaker is better than any other type of breaker for the high voltage level up to 380 kV”, while in 1978, others said, “The minimum oil breaker has survived the air-blast wave, which now belongs to the past, and will undoubtedly not be stifled by $SF_6$ [sulfur hexafluoride] either”. Market forces, however, proved both opinions wrong and the $SF_6$ solution is now more popular than either of its predecessors.

$SF_6$ is an inert gas with very good insulating properties, even at relatively low pressure (ie, 0.5 MPa). This low pressure is crucial because $SF_6$ would liquefy under higher pressures and be unable to interact with the arc. The principle of the $SF_6$ circuit breaker is shown in 6.

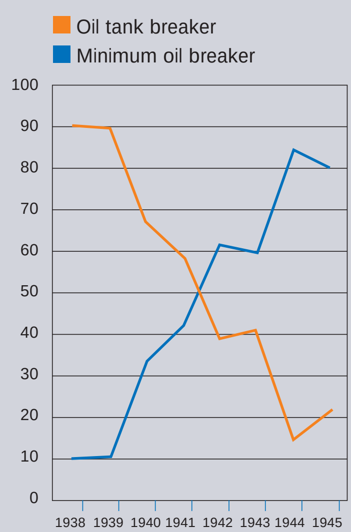
Electrical arcs have enormous energy: their temperature can exceed 50,000°C and pressures up to 100 MPa can be contained within a volume of less than a liter.

The moving contact is connected to a nozzle and a cylinder that forms the piston that compresses the $SF_6$ gas as the contacts move. When the arc is formed, the cold $SF_6$ gas, from the dynamically compressed lower part, can interact with the arc in an axial flow and diffuse its energy.

This device combines a number of beneficial features including low maintenance, clean operation, no external compression, and no exhaust noise. The use of $SF_6$ as a medium has proved extremely popular with customers and engineers. Since 1970, increasing investment has been made in the development of these breakers.

Capitalizing on the advantages of $SF_6$ as a medium, ABB engineers went on to combine it with the self-blast principle, as used in the minimum oil breaker. But the first applications of the self-blast features in an $SF_6$ breaker followed another path, as used in vacuum circuit breakers: using a magnetic field to control the arc. When the contacts are opened, and an arc formed, a magnetic field builds up due to the spiral form of the electrodes. This causes the arc to rotate at high speed, forcing it to mix with the cold $SF_6$ medium, which quickly saps its energy.

5 Sales volumne of oil breakers from ASEA around the year 1940.




Source: Asea Journal 1946, p. 17

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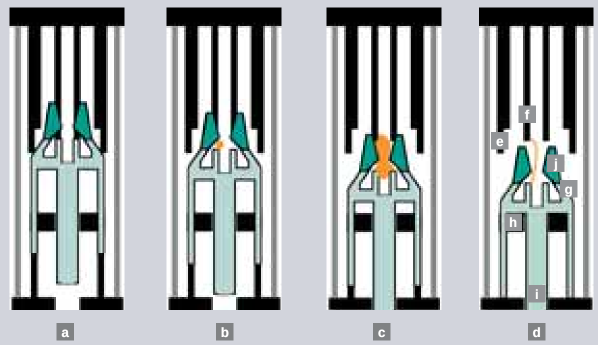
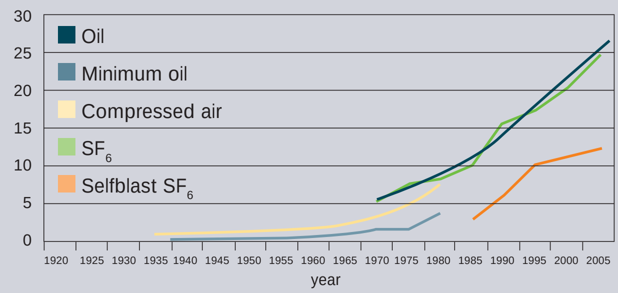
A few years later, the cumulated expertise in arc cooling, gas flow, material ablation and gas insulation gave rise to a lean, new $SF_6$-based circuit breaker. The device contained few moving parts and the contacts needed to move only a small distance before the circuit was broken. This technology was soon combined with puffer breaker features and finally led to ABB's current state-of-the-art circuit breakers, which can manage switching power of more than 25 GVA in a single chamber. This represents a 100-fold increase in performance over the last 80 years 7.

6 Operating sequence of $SF_6$ type breaker.




a closed position, current flows through nominal contact
b opening sequence, arc is formed between short circuit contacts
c contacts moving, piston generates high pressure, at maximum current
d arc close to current zero affected by forced gas flow
e contact for nominal current
f contact for short circuit current
g compression chamber
h Piston
i Hollow contact for exhaust gas
j Nozzle for ultrasonic gas flow

7 Breaker capacity per interrupter of ABB circuit breakers.




**$SF_6$ is an inert gas with very good insulating properties, even at relatively low pressure (ie, 0.5 MPa).**

8 shows a modern Live Tank Breaker (LTB). The energy required for interrupting short-circuit current in this breaker is taken partly from the arc itself. This reduces the operational energy requirements to less than half that of a conventional $SF_6$ puffer-type circuit breaker. Lower energy requirements reduce stress on the breaker and therefore enhance reliability.

8 Live Tank Breaker D for voltage levels up to 170 kV and 40 kA breaking current.

All of the breaker types discussed so far rely on some kind of medium in which the electric arc develops. The vacuum circuit breaker, however, takes a different approach. When live contacts separate in a vacuum, the metal electrodes begin to evaporate and it is this metal vapor that provides a conductive medium for arc formation. Because the electrodes are spiral, a magnetic field is induced in which the arc rotates. The arc is extinguished when the metal vapor recondenses on the electrodes and walls of the breaker chamber.

Since the beginning of the 1980ies, ABB has produced well over a million vacuum interrupters. This high-tech product remains in great demand worldwide. ABB's current product range comprises vacuum interrupters for circuit-breakers from 12 to 40.5 kV, with short-circuit breaking currents up to 63 kA.

## Circuit breakers of the future

The proper management of the electric arc, unavoidable in all the existing circuit breakers, has been studied and understood over the past 100 years. Of course, preventing arc formation would be preferable to managing it, if a new switching principle using power semi-conductors could be devised.

Power electronic devices are widely used in the electricity industry and high-voltage, direct-current (HVDC) systems – a major product range for ABB – are based on the best performing power semiconductors. For this technology to be applied in circuit breakers, the performance of current devices would need to be vastly improved. Current semiconductor technology would allow, at least in principle, a power circuit breaker to be designed, but it would be a highly complex, extremely costly exercise. A fully electronic breaker would not be competitive in today's market.

The history of circuit breaker development shows, however, that the combination of various established technologies in new products has been very successful. ABB is continuing that tradition and combining features of conventional breakers with power electronic devices. Further leaps in performance and development are expected in this field.

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Towards the end of 2006, several important reports were published by prominent organizations on the topic of a sustainable energy future for the world, including action plans and cost estimates. After the Gleneagles G8 summit meeting held in Scotland in July of 2005, Sir Nicholas Stern was appointed to investigate strategies to contain global warming. His report on the "Economics of Climate Change" issued a stern warning to the world of escalating costs if this issue is not tackled now rather than procrastinated further. The World Business Council for Sustainable Development issued its report in October 2006 under the name of "Powering a Sustainable Future". ABB co-chaired this work through the active participation of CEO Fred Kindle. The International Energy Agency, IEA, in its most recent report estimates that unexploited energy efficiency potential offers the single largest opportunity for emissions reductions.

These reports have two things in common: The demand for electricity will keep increasing and end-user energy efficiency improvement is the only short term remedy to contain rising emission levels. IEA calculates that energy efficiency measures can account for between 31 and 53 percent of $CO^2$ emissions reductions by 2050. Technologies to improve the efficiency of energy conversion exist and can be applied cost effectively in all economies and with all end users.

ABB is a major supplier of these technologies. ABB Review will dedicate its next issue to present products and solutions available today that can make a difference in how industry and utility use and produce electricity. The long journey towards the goal of "Powering a Sustainable Future" can start today based on these technologies.