ABB Review

6/99

Advanced control of processing lines in steelworks

New circuit-breakers provide synchronous functionality at distribution level

Measurements prove good performance of axial surface-type condenser

How ABB is meeting EMC requirements on the threshold of the new millennium

A novel analyzer for cooking liquor measurements in pulp mills

ABB REVIEW

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The ABB Review is published six times a year in English, French, German, Spanish and Swedish.

Publisher and Copyright © 1999
ABB Ltd
Zurich/Switzerland

Publisher's Office
ABB Corporate Management Services AG
Rütistrasse 6
CH-5401 Baden
Switzerland
Tel. +41 56 205 48 36
Telefax +41 56 221 22 74
E-mail internet address:
abbreview.chmar@ch.abb.com
Homepage http://www.abb.com/abbreview

Enquiries concerning the editorial content should be addressed to:
The Editor
ABB Review
Rütistrasse 6
CH-5401 Baden
Switzerland

Subscription correspondence should be addressed to the nearest ABB representative or direct to the publisher's office.
Notifications of change of address should include the address label from the most recent issue.

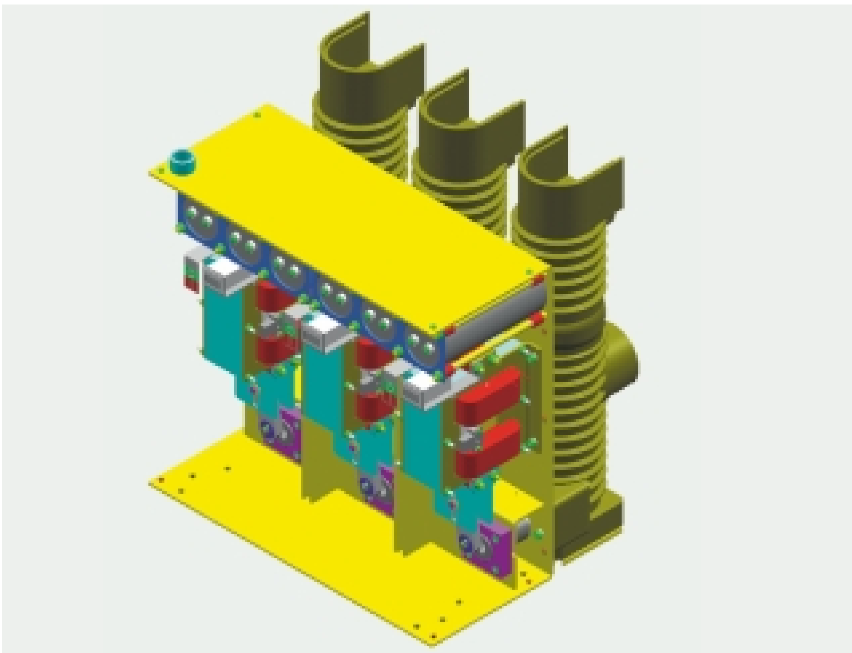
Orders for the ABB Review may be placed direct with the publisher, ABB agents or representatives, or with appointed booksellers.

Subscriptions/copy prices
Annual subscriptions: SFr 110/€ 69
(incl. regular mailing to all countries)
Airmail rates:
Europe plus SFr 35/€ 22
Overseas plus SFr 52/€ 33
Single copies of back issues:
SFr 20/€ 12, incl. mailing
Subscription orders for the next 6 issues can be placed at any time.

Lithography and Printers
Vorarlberger Verlagsanstalt
Aktiengesellschaft
AT-6850 Dornbirn
Austria

The ABB Review is printed on chlorine-free paper.

ISSN: 1013-3119



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THIS ISSUE

Tests carried out on a CB/A axial surface-type steam condenser and vacuum deaeration system in a 180-MW combined cycle facility show that the plant easily meets performance requirements under the test conditions. Evaluation of the measurements verified the design calculations and provided data that will serve as a reliable basis for further development work.

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Electromagnetic compatibility (EMC) is the property of equipment that enables it to operate reliably in its electromagnetic environment without interfering with the operation of other equipment. ABB is able to satisfy not only the legal stipulations, which should be considered as the minimum level of EMC required, but also the most demanding requirements in this extremely challenging field.

Page 32

CLA 2000™ is a novel cooking liquor analyzer that allows more accurate measurement of the liquid concentrations in wood-pulping processes. It addresses environmental issues as well as increased demand for higher wood-pulp yield and quality, while providing data that assist in the process management. Reduced chemical consumption and lower maintenance costs are other benefits of the analyzer.

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Control & automation of annealing and pickling lines

New developments in AC drive technology, including Direct Torque Control, are at the heart of advanced electrical systems developed by ABB for stainless steel treatment lines. Among the system features are operator stations for automated plant control and efficient management of the production data. Powerful software functions not only enable steel producers to control the quantity of produced material more precisely but also provide valuable information about the quality of the finished steel strip. ABB recently supplied all of the electrical and automation equipment for a new annealing and pickling line installed at Baoyong Special Steel in Ningbo, China.

The demands made on the surface quality and thickness of steel strip have increased in recent years. At the same time, operators have had to concentrate on maintaining high annual production rates. To balance these needs, plants have to be equipped with advanced electrical systems featuring dedicated control functions.

One of the most important parts of an integrated steelworks is the cold rolling area, where the coils from the hot rolling mill are processed into steel strip. This area can be divided into two main sections **1**:

- Cold rolling mills for reducing the strip thickness
- Plants for the treatment of the structure/surface of the material and for changing the strip dimensions (*Table 1*)

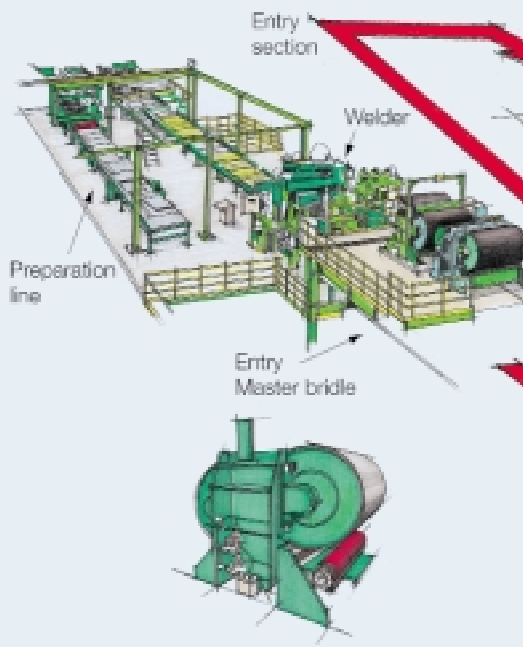
The electrical equipment installed for the strip treatment plant has a large influence on the quality of the finished products. For example, the line control system has to ensure very precise movement of the strip. A standstill in the process section or uncontrolled strip tension can easily cause irreversible damage to the material or loss of production.

Main processing lines

Strip processing lines alter the characteristics, appearance and/or dimensions of flat-rolled products. Typical examples are the galvanizing line, which coats the steel with a layer of corrosion-resistant zinc, the colour coating line, which applies a layer of paint, and the slitting line, which cuts wide coils into narrow strips.

Except for those lines with a shearing section at the exit end, most coil processing lines can be described as continuous coil-to-coil operations. This means that coils of metal are brought to the line entry, uncoiled, fed continuously throughout the treatment process, and recoiled at the exit.

Luca Zanella
Vincenzo Spinelli
ABB Industria SpA



Entry-to exit automation advanced electrical syst

In the cold-rolling area of an integrated steelworks

Continuous operating lines

To ensure that the quality goals are achieved, the process sections have to

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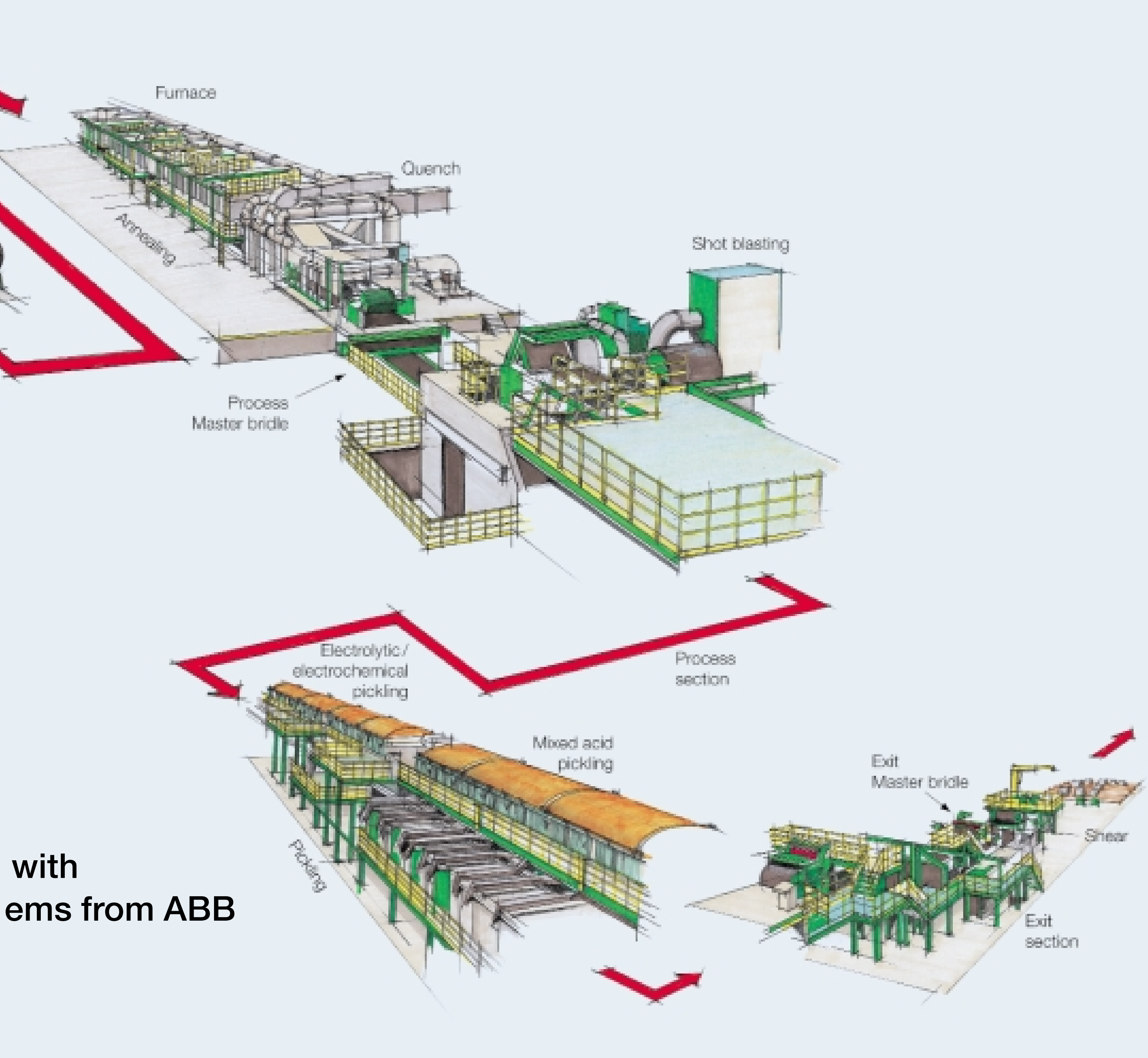


the coils received from the hot rolling mill are processed into strip, which is then passed through the treatment line. **1**

operate at constant speed and the process has to be supervised from beginning to end. After preparation of the coil, eg by removing any damaged outer wraps, the strip is fed into the line. One of the first operations to be performed is the welding of the incoming coil to the tail end of the coil being processed. This is a prerequisite for continuous operation, and requires a strip storage device known as the entry looper. The entry looper, in effect a buffer between the entry and the process area, stores enough strip to keep the processing section operating during the welding. As soon as the looper has emptied, the entry section accelerates to a preselected overspeed to provide more strip to refill it.

The main functions of the exit section are strip rewinding and coil discharging. These are made possible by another looper, which stores the strip coming from the processing section. Also, the exit section is capable of working at overspeed to compensate for the excess strip stored in the exit looper during stops in this section.

Table 1
Plants determining the structure and surface of the material

Surface improvement	Surface treatment/ structural change	Strip dimensions
• Electrolytic tin/chrome lines • Electrolytic cleaning • Galvanizing and aluminizing lines • Coating lines	• Pickling lines • Continuous annealing lines • Combined annealing and pickling • Electrolytic strip degreasing	• Slitting lines • Shearing lines • Recoiling lines

Annealing and pickling line

The annealing and pickling line (APL) is one of the plants requiring a constant material processing time.

To remove the hardness caused by rolling, the strip is first run through the annealing section of the APL. During the annealing process the lattice of the steel is stress-relieved and its structure rearranged. Annealing can be performed in a continuous process in which the strip is passed through a furnace with different heating zones that raise it to an exactly defined temperature and afterwards through cooling zones that gradually cool it down to its exit temperature of about 80 °C (higher temperatures cause the line to be stopped to prevent possible damage to mechanical equipment further along). The temperatures in the heating zones are varied according to the type of steel being treated and the strip gauge and width.

After being annealed the strip is passed through the pickling section to give the material a clean, bright surface. This section consists of tanks containing electrolytic, electrochemical and mixed acid solutions.

Table 2 gives details, including the running speeds and annealing data, of a new APL installed recently by ABB at *Baoyong Special Steel* in Ningbo, China **2**.

Table 2
Specification of the new annealing and pickling line at Baoyong Special Steel in Ningbo, China

Product data	
Strip material	Hot and cold stainless steel (AISI 300–400)
Strip thickness	0.3 mm – 5.0 mm
Strip width	650 mm – 1350 mm
Coil weight	max 31 t
Running characteristics of line	
Threading speed	25 m/min
Entry/exit speed	90 m/min
Process speed	60 m/min
Entry/process/exit acc and dec	
Normal acceleration	$+0.13$ m/s^2
Normal deceleration	-0.13 m/s^2
Fast stoppage	-0.26 m/s^2
Annealing temperatures	
HR 300	1130 °C
CR 300	1090 °C
CR 400	840 °C

Drive control strategy

It is not possible to define a unique control strategy for a continuous processing line that will take account of all the different drive combinations in the various line configurations; this is particularly true in the case of the process section. Nevertheless, it can be done for some of the motor drives.

Normally, it is necessary to isolate the strip tensions in the various sections from each other in order to stop one section from influencing another. This is accomplished by means of speed-controlled bridle rolls. Each section has a master bridle which determines the reference speed; a speed pilot in the entry and exit sections controls the overspeed for the looper operation during stops (eg, for coil welding and finishing operations). When these operations have been completed the speed is adapted again to the process. Normally, there is one bridle operating in underspeed mode (feedbackward regulation) and another in overspeed mode (feedforward regulation), in each case referred to the master bridle of the process. This arrangement, known as indirect tension control, ensures that the required strip speed and tension are maintained. In other words, a bridle not assigned the function of a speed master acts as an indirect tension-controlled drive.

Very precise control of the strip tension is necessary to avoid strip breakage in critical areas. Direct tension control, with load cells mounted directly on the rolls **3**, guarantees this.

Pickling section of the annealing and pickling line at Baoyong Special Steel in Ningbo, China.
The open tanks contain the rectifiers that generate the current flux used to clean the strip surface. **2**

Usually, the speed control of a master bridle is based on load sharing between the two drives of the bridle (*Table 3*). The advantage of this configuration over the solution with one drive as the speed master and the other speed-controlled is that the stability is better during acceleration and deceleration and differences in the roll diameter are compensated for at constant speed.

Indirect tension control with compensation of acceleration and losses is normally used for the coiler and looper. Thus, in the entry and exit section only one bridle is designated the speed master. If there is a side trimmer in the exit section it may have (with respect to the strip direction) one bridle before and one after the side trimmer, the latter acting as master so as to ensure constant speed at the side trimmer.

There is no particular rule for the process section. In general, the speed master should be behind the most critical part (eg, the furnace). If the line has only one process, the speed master will be next to the exit of the process. If there is a stretch leveller in the section, the leveller itself should be the master.

Load cell for direct tension measurement, mounted on the bridle at the entry of the process section **3**

Table 3
Typical drive control in a processing line

Motor	Power range (kW)	Control	Alternative control	Direct Torque Control (DTC)	Compensation
Bridle	20–60	Speed control with torque limitation	Torque control (direct or indirect tension control); option of load sharing and windows control	With pulse generator	Inertia and losses
Looper	80	Torque (tension control); strip tension remains constant during acceleration/deceleration and at constant speed	Speed control during jogging	With pulse generator	Inertia, losses and unbalanced weight
Winder Unwinder	150–400	Torque (indirect tension control) in normal run with coil diameter calculation (torque follows change of diameter value during coiling)	Speed control during threading, jogging, strip tail end positioning	With pulse generator	Inertia and losses
Support roll Squeeze roll Pinch roll	3–15	Window control (no slip between strip and roll: drive runs at deadband speed so that drive speed is always similar to material speed)		No pulse generator	Inertia and losses

Electrical solutions

When procuring electrical equipment for a plant, consideration needs to be given not only to the first-time cost of the equipment but also to the total cost over its lifetime. This has to take into account factors such as efficiency, energy consumption, spare parts and maintenance. The industry's preference in the past for adjustable-speed DC drives, which easily achieve a good torque and speed response, is giving way to a trend towards AC drives. This has come about as a result of modern electronic converters offering the same speed accuracy and fast torque response, but with the added plus that the AC motors allow a major cost saving due to their simpler construction and high reliability, even in harsh environments, and easier maintenance.

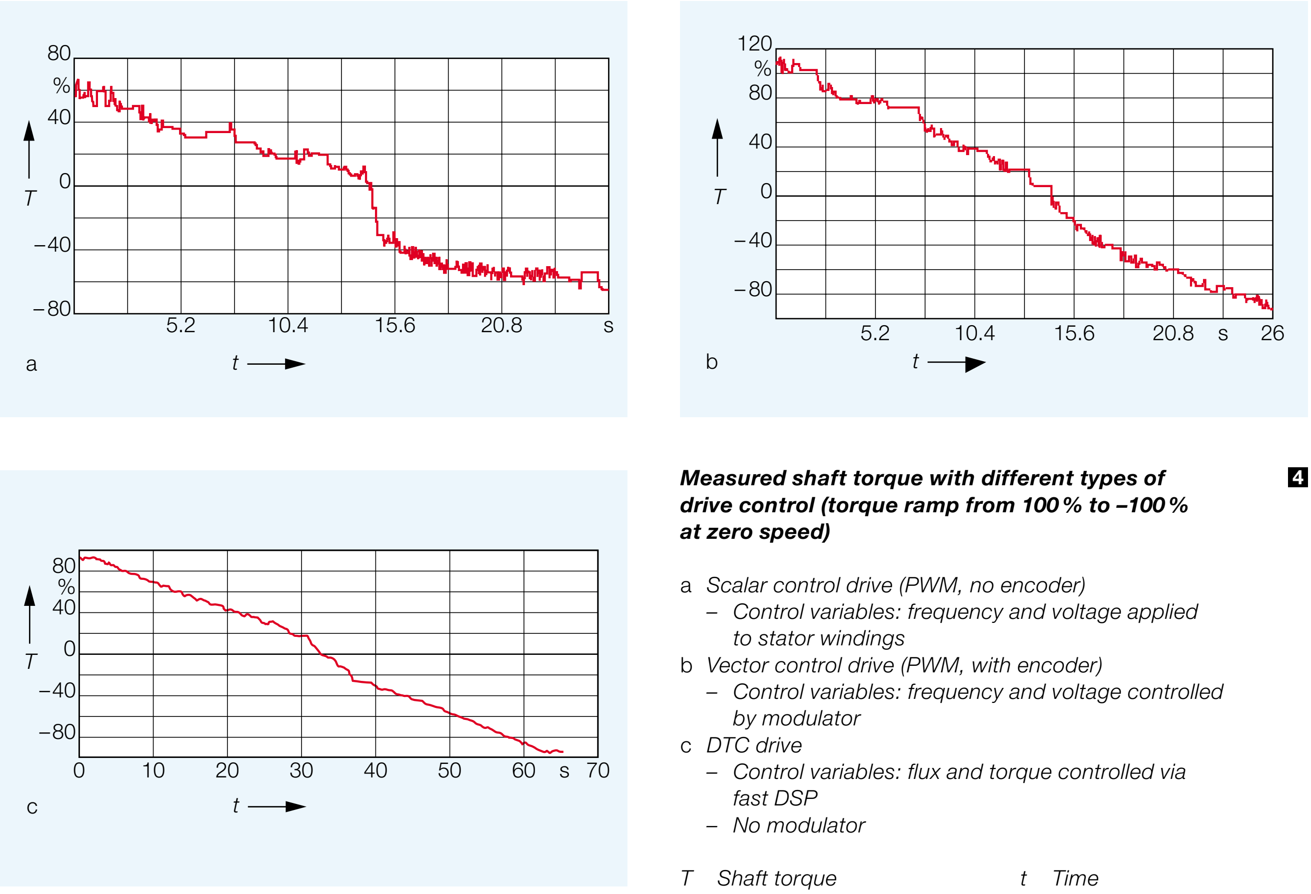
Table 4
Static and dynamic speed error achieved with DTC, scalar control and vector control

Speed error	Scalar control (no encoder)	Vector control (with encoder)	DTC (no encoder)	DTC (with encoder)
Static	± 1 to 3 %	± 0.01 %	± 0.1 to 0.5 %	± 0.01 %
Dynamic	3%	0.3%	0.4%	0.2%

Direct torque control

Direct Torque Control (DTC) [1, 2, 3] is the motor control platform launched by ABB in 1994 as the universal solution for LV drive applications and recently adapted for MV applications. This technology is also used to control the induction motors delivered to the new annealing and pickling line of Baoyong Special Steel in Ningbo, China.

Unlike traditional vector control, in which the parameters affecting the voltage and frequency (eg, the motor current and flux) are measured indirectly and a pulse encoder has to constantly provide new data to obtain a real degree of accuracy, DTC allows fast and flexible control of the machine without encoder feedback. Also, the variables used in flux vector control are controlled by a modulator, which delays the responsiveness of the motor to changes in torque and speed. DTC on



Measured shaft torque with different types of drive control (torque ramp from 100 % to –100 % at zero speed) **4**

a Scalar control drive (PWM, no encoder)
– Control variables: frequency and voltage applied to stator windings
b Vector control drive (PWM, with encoder)
– Control variables: frequency and voltage controlled by modulator
c DTC drive
– Control variables: flux and torque controlled via fast DSP
– No modulator

T Shaft torque *t Time*

the other hand uses advanced motor theory to calculate the torque directly without the need for a modulator; the control variables are the stator flux and the motor torque.

When DTC open-loop drives are installed, high dynamic performance (speed accuracy and torque control) is possible in many cases without having to use a tachometer. Where a higher accuracy is required, closed-loop DTC drives are employed, but the feedback device may be less accurate and therefore cheaper than the one used in traditional flux vector drives as the speed error and not the rotor position is known by the drive. In processing lines such as the APL described, the main motors used to transport material (in the bridles, loopers, uncoilers, coilers) are fitted with pulse generators.

The control variables in DTC are:

- Stator flux
- Torque, calculated on the basis of the flux and stator current
- Comparison of the flux amplitude and torque deviation with given references; the information this provides is sufficient to determine the optimum voltage vector at each instant

The high precision of the mathematical motor model makes speed feedback unnecessary.

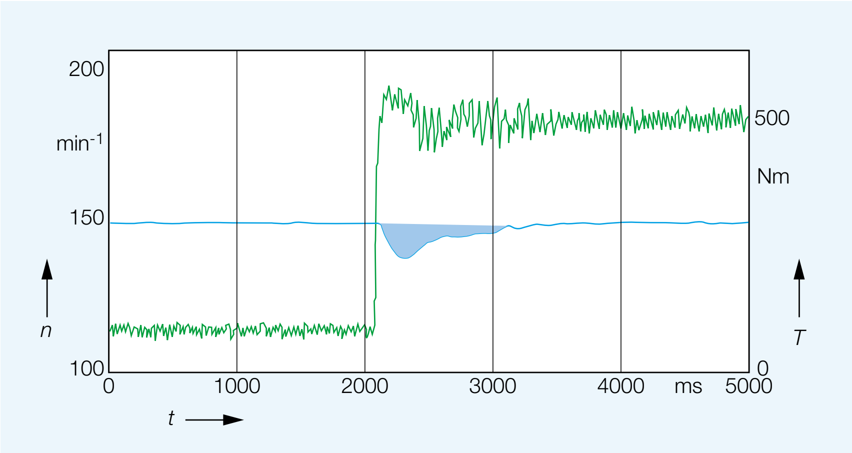
Combining high-speed signal processing with the advanced mathematical model has produced a 25 µs high-performance control loop that ensures accurate torque control and low oscillation levels. The resulting very fast torque response makes the DTC AC drive twice as fast as flux vector AC drives and at least ten times faster than open-loop AC drives with scalar control.

Other benefits in the torque control area include very precise torque control at low speeds, even down to zero, and full torque at zero speed. Measurements of shaft torque (with a torque ramp from 100% to –100 % at zero speed) for different drive controls are shown in **4**.

With DTC the dynamic speed accuracy is at least eight times better than with open-loop AC drives, and static speed control accuracy is twice as good as with the existing general-purpose AC drives (*Table 4*) **5**.

Automation systems

Modern automation systems based on an open system architecture provide user-friendly, reliable tools that support the operator in his daily work. Such systems feature a combination of field controls and higher-level information that makes it easy to interchange data between the Open Control System (OCS) and the Manufac-



Direct Torque Control (DTC) and dynamic accuracy **5**

n *Speed*
T *Torque*
t *Time*

Blue *Speed*
Green *Torque*

turing Execution System (MES) **6**. By combining these concepts, a plant automation system evolves with capabilities that extend from single motor control to overall plant control.

OCS operator stations

Advant OCS operator stations have direct access to a database in which all the data related to the processing line is stored. Located at the entry and exit pulpits of the line, the stations manage alarm reports and information arriving from each section, allowing the status of the plant to be kept under control. For example, the general starting conditions, motor torque and motor speed can be viewed and preset from these stations.

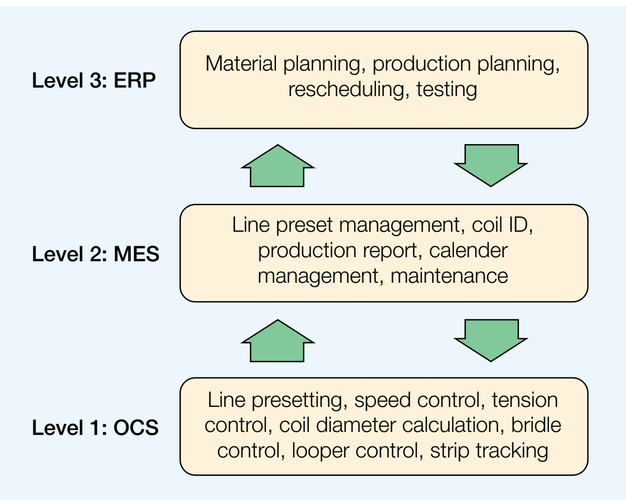
Strip tracking is one of the main functions provided by Advant OCS **7**. It assists the operator with routine work by keeping track of the coil welding so that the position of the strip inside the line and the amount of coil threaded in the entry section and rewound at the exit are always known.

> **ABB Advant® Open Control System**
> With its Advant® Open Control System (OCS), ABB offers a standard, state-of-the-art platform with open system architecture for the automation of industrial processes. The system is characterized throughout by an object-oriented and distributed structure, high-performance operator stations, very high availability and ease of maintenance. All process and operator stations are linked by a system-bus. The process control stations communicate with I/O units by means of field buses. Every stage in the industrial process can be controlled and monitored from each of the process operator stations.

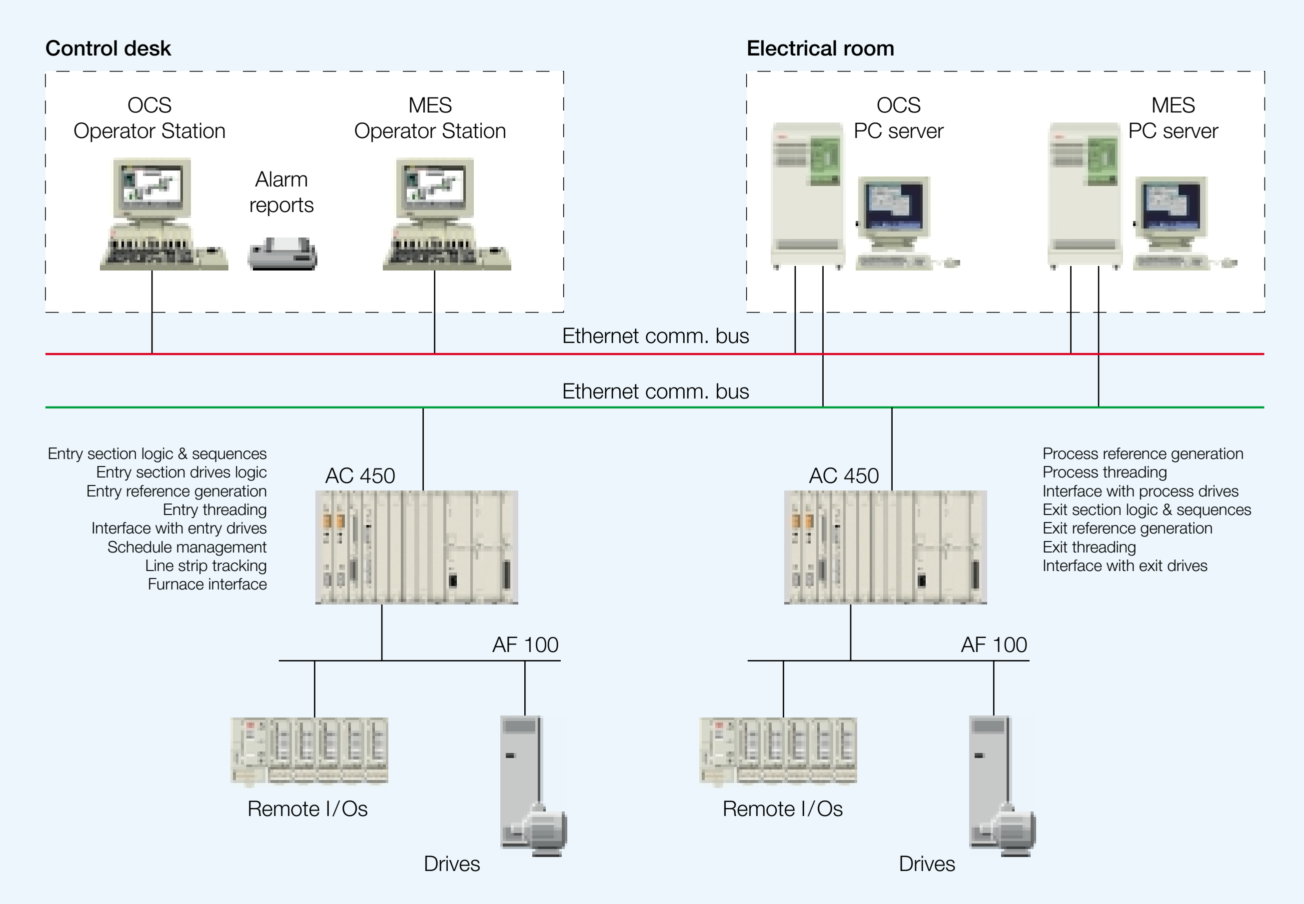
Standard ABB solution

Programmable logic controllers manage the exchange of signals between the different process sections. The current

Main functions performed by the Open Control System (OCS), Manufacturing Execution System (MES) and Enterprise Resource Planning (ERP) system **6**



OCS: strip tracking display showing the reference and actual values of speed and tension in different sections of the line. Also shown is information on the incoming and outgoing coils (eg, the coil ID and remaining strip length). **7**



Automation layout with two multi-CPU PLCs in control of the whole line. From the control desk it is possible to view all the operations taking place in the line. **8**

standard ABB solution for a strip processing line consists of two PLCs (AC450 RMC) **8** dedicated to applications in the metallurgical sector. A wide choice of standardized functions and ready-made software modules makes it easy to find reliable solutions that meet customers' needs.

The first multi-CPU AC450 controls the entry section, the tracking and the presetting functions, while the second PLC interfaces with the process and exit sections. To relieve the CPU load of the PLCs some functions are implemented on the motor drives; these incorporate the majority of the application software for motor control. The large drive systems are, in fact, linked through a fast, dedicated fieldbus (AF100) via a control unit called the Application Controller (APC). Software running on the APC includes modules for speed control, current control and tension control. Remote I/O devices communicate through the AF100 with the overriding control CPU.

The standard overall control system function covers the generation of all sequences, velocity and acceleration references for the drives, and the signals for starting and stopping the line. Application-specific modifications are made according to the project requirements.

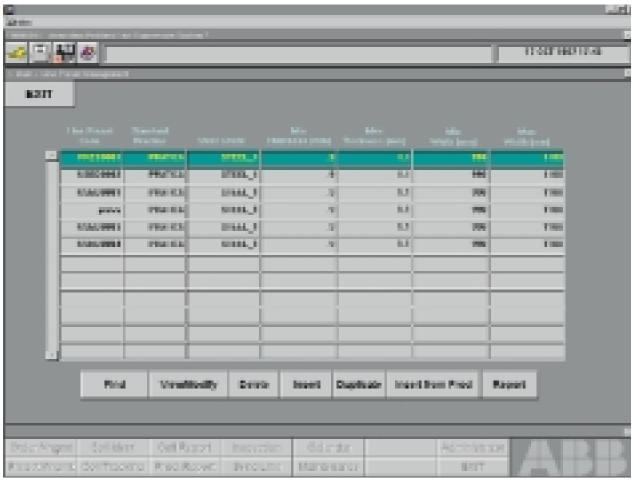
Manufacturing Execution System

Quality control depends not only on accurate control of the technological parameters of the strip but also on overall control of the production process. The necessary coordination is achieved by means of Manufacturing Execution System (MES) functions, being divided into operator functions and process functions.

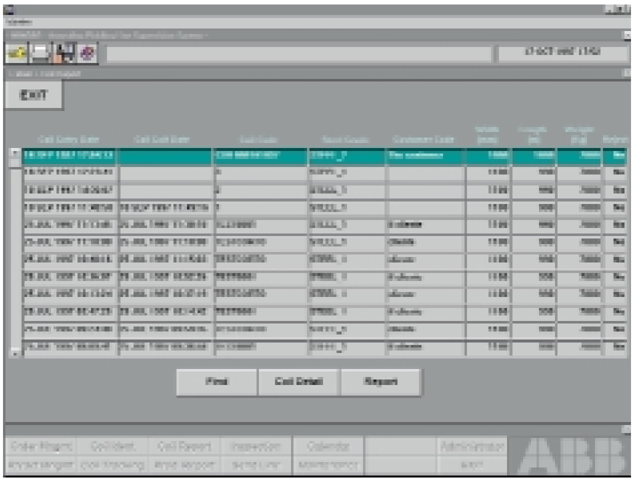
Operator functions

These functions are as follows:

- *Order management*, giving the list of coils to be worked and detailing for each coil its dimensional data, main characteristics (coil code, steel grade identification for furnace and pickling, customer code) and required final characteristics.
- *Line preset management* **9**, comprising a set of data used to set the line up before starting production; preparations for all the electrical and mechani-



MES: line preset management. All the data for line set-up are entered here. **9**



MES: coil report. This provides information on the technological parameters and quality of the produced strip. **10**

cal devices are based on the order data. Coil data given by the order management and line preset functions assigned to the coil constitute the preset data sent to the OCS for correct coil processing.

- *Coil reporting* **10**, with displays and print-outs of data on worked coils. The main displays are the quality product report (thickness, flatness, elongation data) and the technological product report (furnace, pickling, thickness, flatness, elongation distribution data for the process technology engineer).
- *Production reporting*, showing the number of coils produced and the work shifts in the plant (production reports can be displayed on a shift, daily and monthly basis). Reporting of the plant time distribution (how long the plant has been in operation and how long at standstill) and the pickling consumption is also possible.
- *Maintenance reporting*, showing the actual operating time of the mechanical and electrical equipment.

Process functions

These functions are automatically activated by the system whenever a message is received or something occurs in the plant.

- *Material tracking*, allowing monitoring of the position of the coil in each section of the line.
- *Data acquisition*, for collecting information from the OCS about the uncoiler and recoiler, tension and process sections, as well as for archiving in the system database.

APL automation systems normally make use of mathematical models that control the processing area with high precision and have a direct effect on the overall strip quality. In the case of the furnace, for example, the mathematical model uses the line speed, type of steel, strip width and thickness as information when converting the annealing curve characteristics into working parameters. A model may also be provided for the pickling area, for example to precisely control the acid dosing needed to obtain a clean, bright surface.

Conclusions

Adjustable-speed AC drives featuring advanced DTC technology and flexible control systems are destined to make a significant contribution to process line developments in the metallurgical industry. Steel producers benefit from the use of such powerful tools not only by being able to control more precisely the quantity of produced material but also due to the important information they provide about the quality of the finished strip.

Reference

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Authors

Luca Zanella
Vincenzo Spinelli
ABB Industria SpA
IT-20099 Sesto San Giovanni (Mi)
Italy
Telefax: +39 02 262 32 480
E-mail:
luca.zanella@it.abb.com
vincenzo.spinelli@it.abb.com

Synchronous MV circuit-breaker with magnetic drive and electronic control

New synchronous circuit-breakers developed by ABB can be fully integrated in medium-voltage switchgear in order to provide synchronous functionality at the distribution level. Equipped with fully configurable software, such circuit-breakers offer flexible solutions that can be used in all types of network, eg to reduce switching transients. They extend the range of synchronous operation from capacitor bank switching to all distribution circuit-breaker applications, including the synchronous interruption of short-circuit currents. Advantages of the new breakers include high quality and reliability over their service life, reduced maintenance, improved availability and service continuity, as well as a potential cost-saving in the increasing number of applications in which power quality is important. By allowing networks to be simplified, they also help to reduce the overall power system costs.

In 1997 ABB introduced a new series of medium-voltage circuit-breakers with a magnetic drive instead of a spring-based operating mechanism [1]. This solution soon proved to be much more reliable than its predecessor. Following up on the success of the magnetic drive, ABB has now developed a new controlled switching technology which will allow the closing and opening operations to be synchronized with the power network.

Synchronous switching, also called 'point on the wave' switching, is a well-known concept [2,3], being used particularly in high-voltage applications to avoid or reduce switching transients and their power network disturbances.

The synchronous circuit-breaker has several important advantages over conventional switching equipment, eg:

- Transient stresses acting on network components are strongly reduced, enhancing reliability.
- The network exhibits a higher power quality.
- The electrical lifetime and performance of the circuit-breaker are improved.
- The network design can be simplified, thereby reducing the cost of the overall system.

Carlo Cereda
ABB SACE TMS

Carlo Gemme
ABB Ricerca SpA

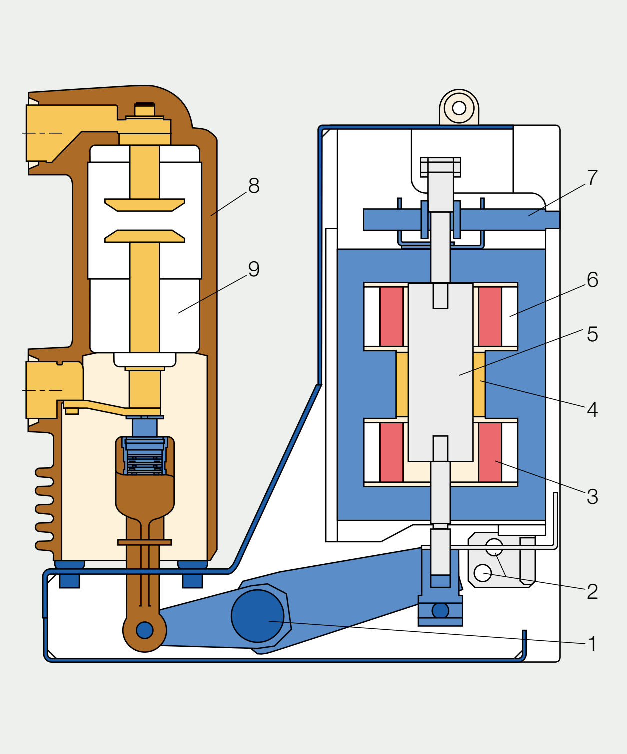
Christian Reuber
ABB Calor Emag Mittelspannung GmbH

Electromechanical system

Manufacturers of synchronous circuit-breakers with a spring-based mechanism rely on the behaviour of the opening/closing operation being predictable. This means that the mechanism has to be designed with high excess energy and show minimal signs of wear and friction over its lifetime. It is also critical to keep the environmental influences under control. Extensive laboratory tests are therefore necessary, leading to algorithms that have to be implemented in an electronic controller.

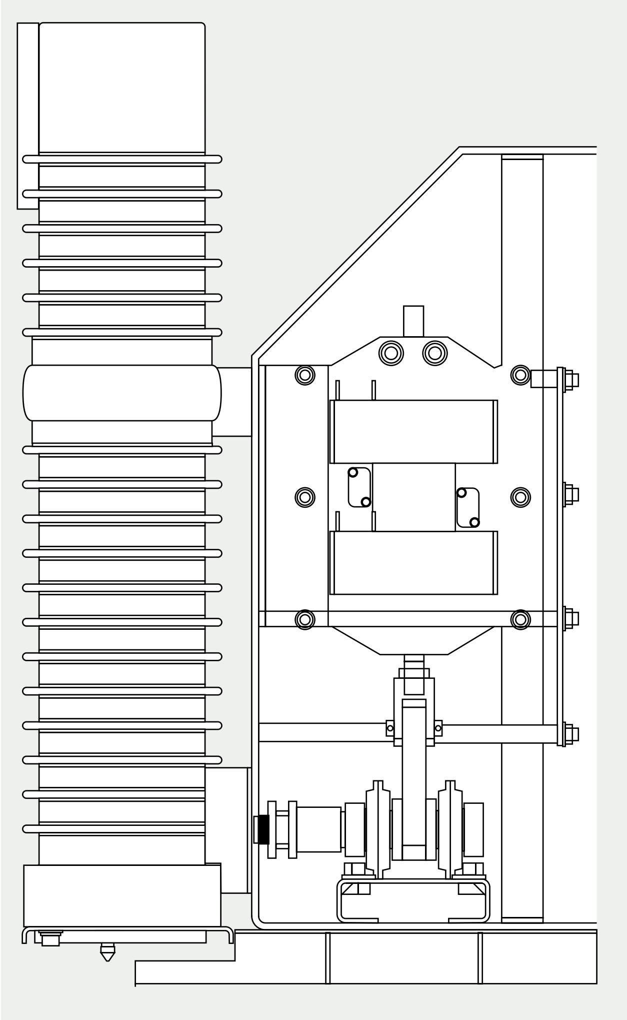
Not even all these features will ensure reliable behaviour, since the motion of the spring-based mechanism cannot be influenced after it has been released. A magnetic actuator, on the other hand, allows the adaptive algorithm to be implemented in a closed-loop control configuration. The motion can then be controlled and the influence of temperature, aging, etc, compensated for, guaranteeing that the operating time will remain stable in the long term.

Medium-voltage circuit-breakers nowadays usually consist of three mechanically connected poles and one drive. The drive can be a mechanical spring type or an electromagnetic actuator. Controlled switching for a very wide range of applications requires an individual drive for each pole. This is much easier to achieve with a magnetic actuator than with a mechanical drive. Furthermore, the repeatability of a magnetic drive is much better due to its smaller number of mechanical parts.



Section through the operating mechanism and pole compartment of a vacuum circuit-breaker **1**

1 *Lever shaft*
2 *Proximity sensors*
3 *Closing coil*
4 *Permanent magnets*
5 *Plunger*
6 *Opening coil*
7 *Emergency manual opening*
8 *Epoxy resin enclosure*
9 *Vacuum interrupter*



Section through the operating mechanism and pole compartment of an SF_6 gas-insulated circuit-breaker **2**

1 shows the simple mechanical construction of a vacuum circuit-breaker, in which the pole is connected to the actuator by a lever shaft. The SF_6 gas-insulated circuit-breaker shown in **2** has a similar mechanical structure, the actuator turning a shaft that leads into the SF_6 compartment of the pole. Inside the pole this rotational movement is transformed into a linear movement, which drives the moving contact. These principles are proven and well-established for non-synchronized breakers, which have one actuator driving all three poles in parallel.

The arrangement for individually driven poles is shown in **3** for the SF_6 circuit-breaker and in **4** for the vacuum circuit-breaker. Magnetic actuators allow a much simpler and more compact design than a mechanical drive. The SF_6 circuit-breaker is based on H Brea King poles manufactured by ABB SACE TMS, the vacuum circuit-breaker using VM1 poles. The vacuum interrupters of the VM1 poles, from ABB Calor Emag Mittelspannung GmbH in Germany, are embedded in epoxy resin to protect them against mechanical impact and pollution.

Synchronism with the network

A synchronous circuit-breaker (SCB) is a breaker which can carry out operations which are synchronized with network voltage or current signals, irrespective of when the starting signal is given and whether it is given manually or by remote control.

5 shows how a synchronous circuit-breaker should behave during a closing operation:

- The red line indicates the asynchronous closing signal sent to the circuit-breaker by the user or the control/protection systems.
- The green line shows the closing signal sent by the control electronics to the actuator, synchronized with the voltage signal or current signal.

- The brown line shows the closing instant when the voltage across the circuit-breaker is zero.

The task of the control electronics is to keep the operating time as constant as possible. To do this it must feature automatic adaptation as well as real-time closed loop control. Equipped with this capability, it will adhere to the specified tolerances even when there are changes in the ambient temperature, capacitor charge or any other relevant parameter. By automatically compensating for contact wear, the control electronics ensures that the contacts always open or close at the right instant.

Switching time tolerance

The basic function of the SCB is to perform switching operations with high reliability in a pre-defined time such that the expected reduction in transients is guaranteed, and to do this over its service life.

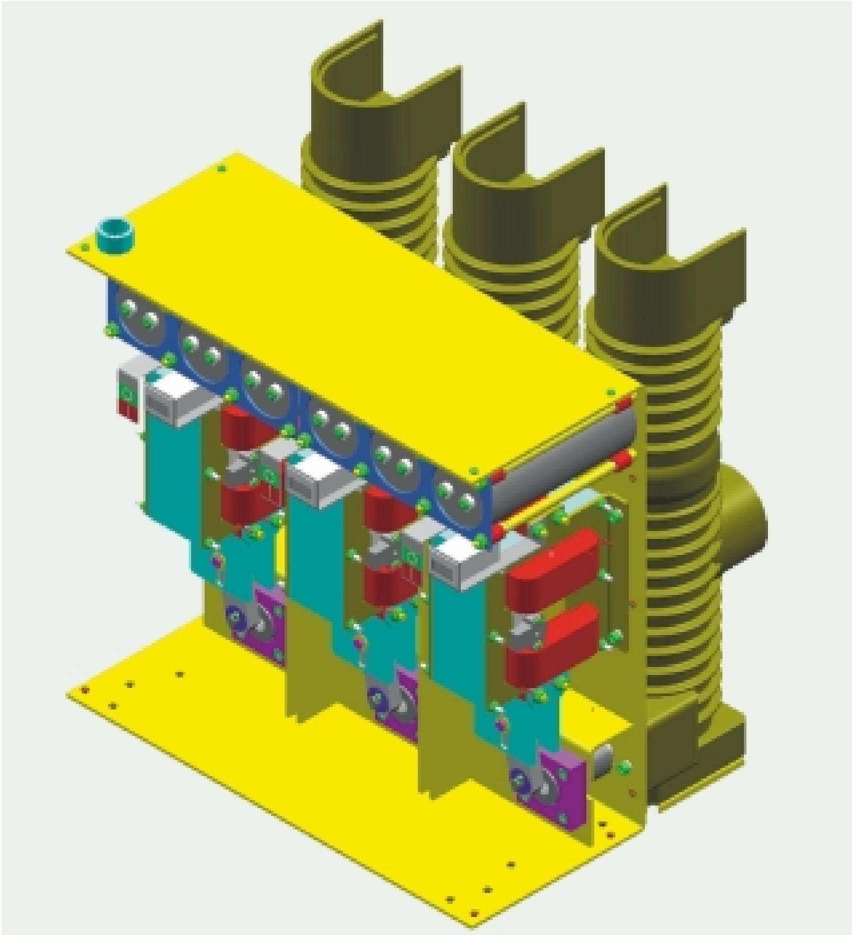
The switching time tolerance of the described SCB has the following maximum values:

± 1 ms for the closing operation
± 2 ms for the opening operation

Whereas the second value is mainly of importance (although not only) to the circuit-breaker manufacturer, the first value has a wider significance, being defined in the literature as the minimum value required for equal or better closing-transient behaviour than when the standard means for reducing such transients are used (*Table 1*) [4].

In order to guarantee these values over the complete lifetime of the circuit-breaker, the factory tests are carried out with a narrower tolerance range:

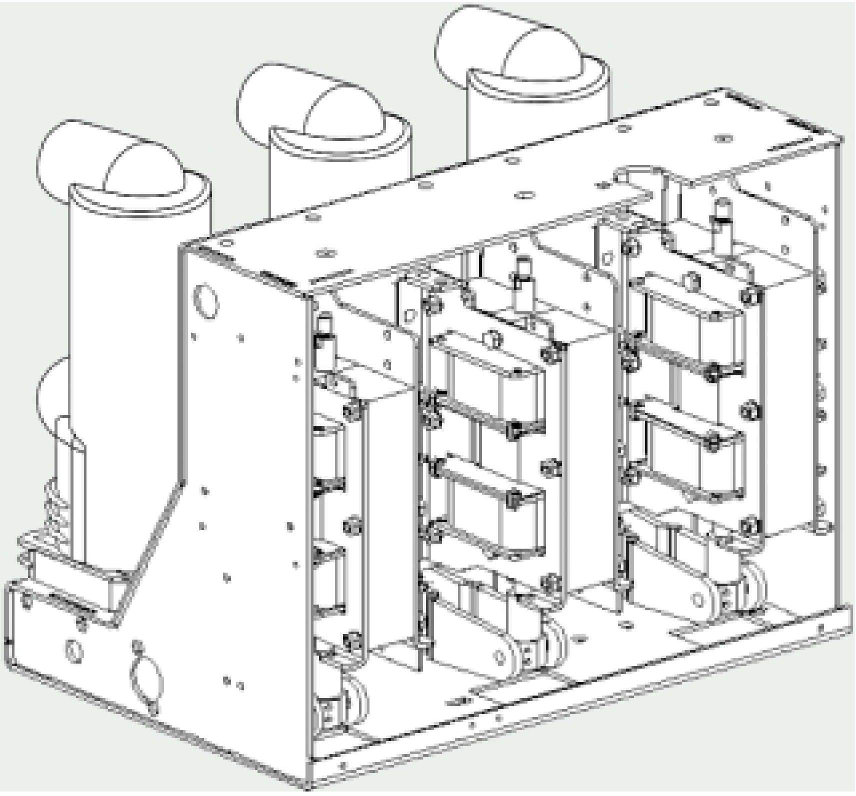
± 0.2 ms for the closing operation
± 1 ms for the opening operation



Arrangement of the actuators and poles of an SF_6 gas-insulated synchronous circuit-breaker **3**

Table 1
Comparison of methods used to reduce transients

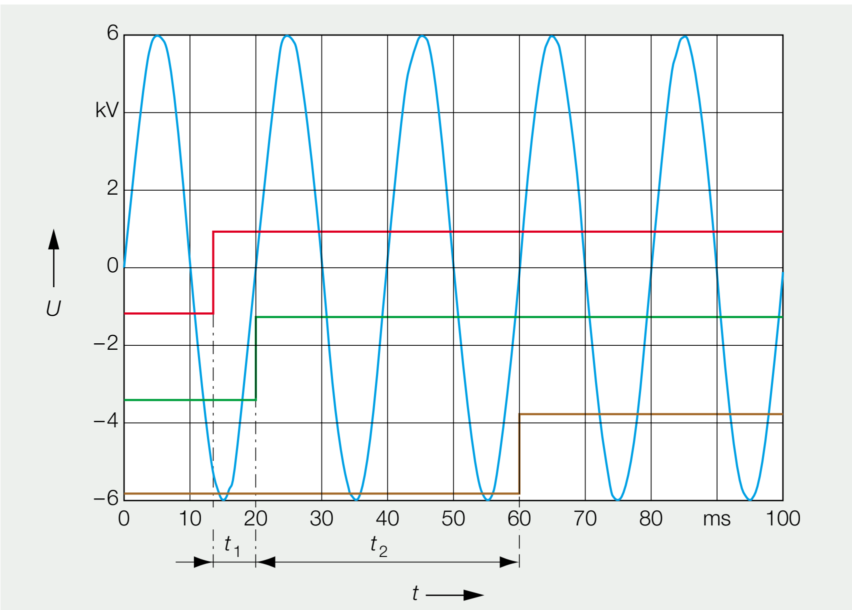
Transient control achieved with	Advantages	Disadvantages
Fixed inductor	Easy to employ Effective for reducing current	Losses & noise Life cost
Pre-insertion resistor	Inserted for short time prior to switching No losses	Complicated, low reliability
Pre-insertion inductor	Inserted for short time prior to switching No losses More effective than fixed inductor	Complicated, low reliability
Synchronous circuit-breaker (SCB)	Effective for reducing *I* and *U* during opening and closing operations Reduced breaker wear	Reliability and consistency problems with traditional SCB solution; problems overcome with new SCB



Arrangement of the actuators and poles of a vacuum synchronous circuit-breaker **4**

Typical closing operation with a synchronous circuit-breaker **5**

U	*Network voltage*	Red	*Asynchronous closing signal*
t	*Time*	Green	*Closing signal, synchronized with voltage or current signal*
t_1	*Synchronizing delay*		
t_2	*Operating time*	Brown	*Closing instant at zero*



Design of the synchronous circuit-breaker

6 shows the arrangement of the SCB control electronics. The signal processing and timing unit is the part of the SCB that handles the voltage and current signals. It receives the command to start the close/open operation and decides when the signal to open or close the following unit has to be given. The system controlling the pole operation checks that it is carried out within the given tolerance time range.

Control electronics hardware

7 shows details of the architecture of the control electronics. The signal processor and timing controller unit checks the power network currents and voltages and also manages the operation command. The control unit is interfaced with the magnetic actuators via the switching unit and the coil current sensors; it also controls the circuit-breaker poles by means of position sensor X.

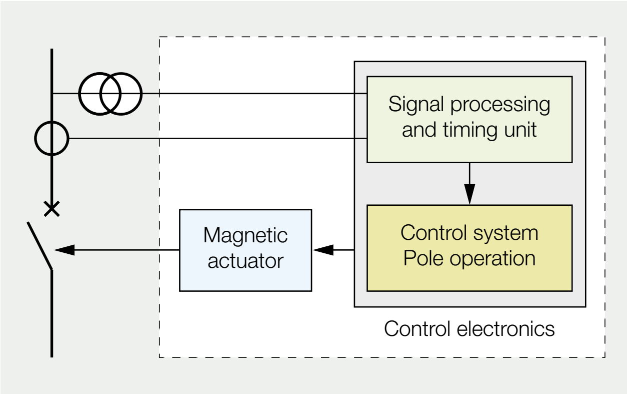
Control electronics software

The control electronics software can be divided into two main parts:

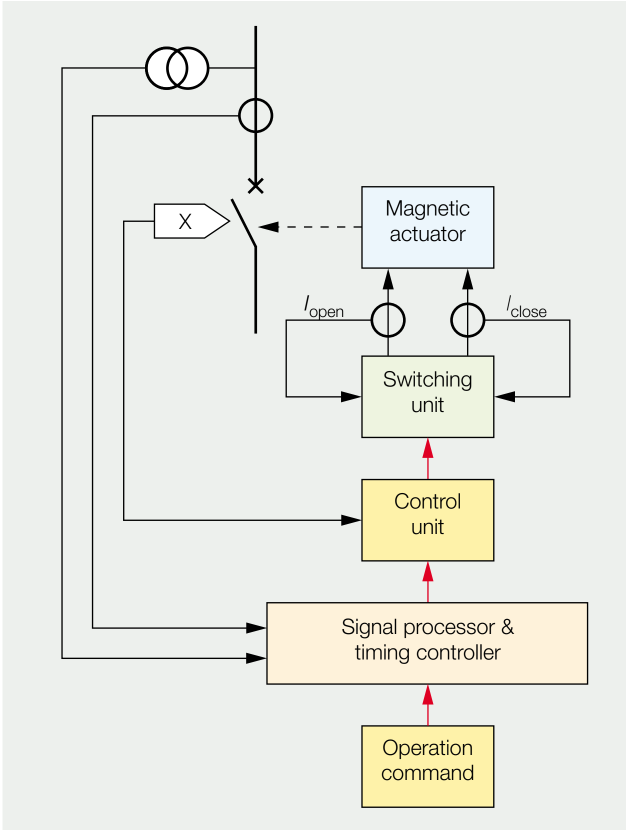
- The system software, which controls the interface with the hardware resources (digital signal processor core, 'on-chip' and external peripherals) and the time scheduling for the application software.
- The application software, which is responsible for the circuit-breaker position control, network quantities, zero-crossing calculation and man-machine interface.

Control unit functionality: application software

The main task of the control unit is to ensure that switching operations take place in the pre-assigned time.



Simple block diagram of the synchronous circuit-breaker control electronics **6**



Architecture of the synchronous circuit-breaker control electronics **7**

X *Position sensor*

Two phases are involved:

1) The current flows through the coil, charging the magnetic actuator, but the circuit-breaker pole does not yet move. This phase of the operation cannot be controlled directly by the software.
2) The pole starts to move and is 'guided' to make sure that the operation takes place at the correct time. This phase can be adapted within a certain range.

User-benefits of synchronous circuit-breakers

Advantages of reducing transients

Switching transients cause a variety of disturbances in distribution power systems. They range from poor power quality through untimely tripping of protection to unacceptable overvoltages, possibly causing severe damage and premature failure. While current transients are restricted to the switch location, transient overvoltages travel to remote locations, possibly affecting other users and propagating to different voltage levels.

Installing an SCB greatly reduces the stresses, overcurrent as well as overvoltage, that the network components experience during closing and opening operations under load. This has significant advantages, including higher power quality and increased system reliability.

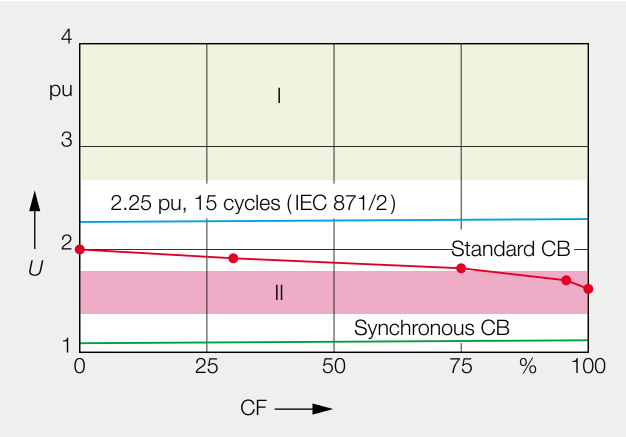
Network component stress is reduced

In the following, the effect of the reduced stress is evaluated for capacitor banks. Similar conclusions can be drawn for other components, eg insulation aging in cable and transformers, etc.

Capacitors are designed and manufactured to withstand the service rated conditions with a large margin. This capability is checked by type-testing in accordance with the requirements in IEC 871-2. According to this standard, switching overvoltage stresses have the highest influence on the aging of the capacitor dielectric and component failure modes. **8** shows the possible stresses experienced by capacitors as a consequence of switching operations with a standard circuit-breaker and with a synchronous circuit-breaker. It can be seen that the standard breaker generates overvoltages above the partial discharge inception voltage (PDIV), while the SCB limits the overvoltages to values below this level.

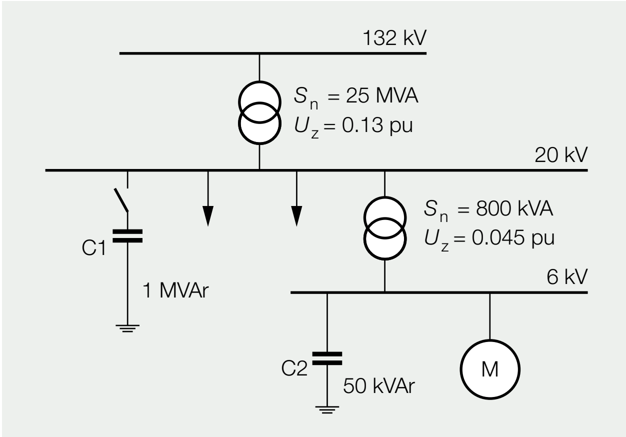
Voltage magnification phenomena or restrikes generate voltages in the area above the 2.6 pu stress level; this is much higher than the values used in endurance tests.

It is clear that limiting the closing transients to a value well below the PDIV for all the expected operating temperatures and



Voltage (U) versus cumulated frequency of overvoltages (CF) generated by standard and synchronous circuit-breakers **8**

I *Restrikes, magnifications*
II *Partial discharge inception voltage*



Circuit diagram showing voltage magnification caused by transients generated by switching loads **9**

C1 *Capacitor bank 1, switched*
C2 *Capacitor bank 2, exposed to voltage magnification*
M *Motor*
S_n *Apparent power*
U_z *Impedance voltage*

reducing the restrike probability to virtually zero will have a beneficial effect on the service life of the insulation. Such a solution totally removes the partial discharge failure mechanism and greatly reduces the electrical aging processes occurring during transients.

Voltage magnification

Transients generated by switching loads can cause resonances that lead to worse transients, called 'voltage magnification', in other sections of the network. This is especially the case with capacitor bank switching transients, which propagate to other voltage levels (MV or LV) when the natural frequencies of two coupled parts of the network are equal or similar, causing overvoltages of up to 4 pu at the remote bank location **9**, **10**.

When an SCB is used, the overvoltages caused by switching loads (especially capacitor banks) can be drastically reduced. The advantages of this are highly significant at the medium-voltage and low-voltage levels, where such overvoltages can easily lead to dielectric faults.

Circuit-breaker electric life enhancement

The electrical service life of a circuit-breaker depends mainly on the arcing energy the breaker is subjected to. This is because of the relationship between the electrical stress and the arcing energy that the interrupters have been exposed to, resulting in contact wear, dielectric stress, overtemperature and overpressure, gas wear, etc. Reducing the arcing energy by operating each phase independently and reducing the arcing time therefore lowers these forms of stress. The expected service life of the circuit-breaker is thus extended through an increase in its electrical life, minimizing the thermal requirements of the interrupter as well as the mechanical requirements of the drive actuator. In addition, synchronous opening of fault currents can increase the interrupting capacity of the circuit-breaker.

Taking the electrical endurance test in IEC 56 as reference, it can be said that the SCB allows a reduction in the electrical stress of at least 50 % for both vacuum and SF_6 interrupting technologies in the worst-case situation.

Considerable economic advantage can be derived from a reduction in circuit-breaker wear and therefore increased lifetime, particularly for applications in which rated current is interrupted very frequently and reconditioning or replacement of the breaker poles has to be scheduled on a yearly basis.

Restrike performance

Improvements made over the years to traditional circuit-breaker technology have greatly reduced the probability of restrikes. However, as the switching frequency can be high in industrial networks, the probability that overvoltages will occur cannot be neglected.

It also has to be said that restrikes sometimes occur in service despite the use of switching devices which are 'restrike free' as defined in the specifications. To take account of this the IEC 56 draft, which is currently under revision, introduces a new concept: 'As all circuit-breakers have a certain restrike probability in service, it is not possible to define a restrike-free circuit-breaker. It appears to be more logical to introduce the notion of a restrike performance in service.'

The basic nature of a restrike transient is identical to that of inrush transients, but, due to the increased magnitude, it may be damaging to power system equipment and make heavy demands on the switching device.

Synchronization enhances the 'restrike-free' capabilities of circuit-breakers by opening the poles independently long before the natural current zero occurs. Thus, although the total arcing time and energy are minimized, a certain arcing time is provided to ensure proper contact separation and the dielectric strength needed at the time of maximum TRV, essentially eliminating reignitions and restrikes as well as the associated overvoltages.

Reliability

The reduced stress experienced by the circuit-breaker during switching operations leads to higher reliability. Although breaker failures play only a minor role in the frequency of network failures, they typically have severe consequences because of the loss of selectivity.

The improved restrike performance translates into even lower circuit-breaker stress and a smaller risk of damage to the switching equipment and other network components.

The SCB therefore has an additional beneficial impact on the network and on the supply reliability and power quality.

Power quality

In today's competitive energy markets, power quality is becoming an important performance indicator. The increasing use of power electronics means that transients, once considered as acceptable minor variations, may give rise to unexpected failure modes, leading ultimately to a significant loss of industrial production.

Adjustable-speed drive tripping

Adjustable-speed drives (ASDs) are being used increasingly in industry to improve the efficiency and flexibility of motor applications.

The tripping of ASD overvoltage protection is often referred to as 'nuisance tripping', since it may occur day after day, often at the same time. The fact that capacitors connected to the MV busbar are operated at least daily means that nuisance tripping is also a potential cause of frequent standstills. Another problem is that ASDs often operate in critical process control environments, so nuisance tripping can be very disruptive and potentially costly. Even when very conservative failure rates are assumed, the total cost of tripping can easily be several times the cost of installing a synchronous circuit-breaker.

Reduction of transformer inrush current

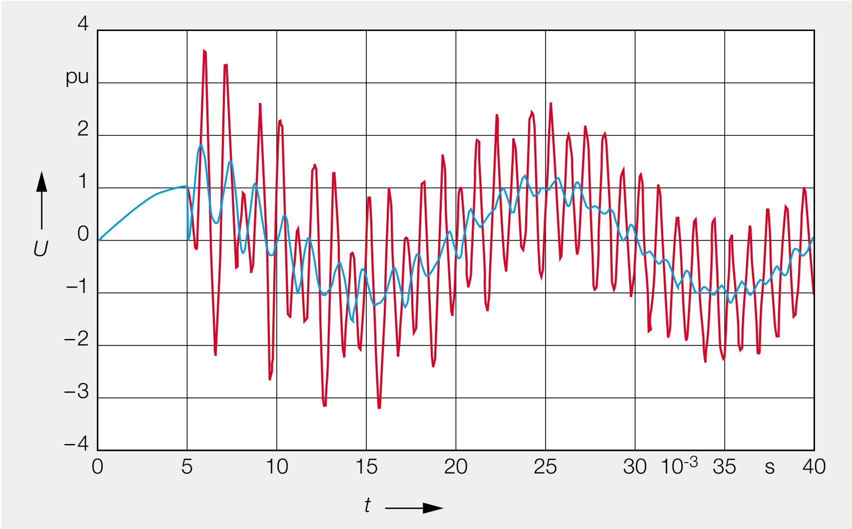
The use of an SCB can greatly reduce the inrush current when a transformer is energized, thus avoiding the statistical occurrence of protection tripping and other problems related to the heavy harmonic content of inrush currents.

Optimum closing strategies have been evaluated on the basis of the residual flux that needs to be considered when energizing a transformer. In such cases, it is necessary to know the residual flux after the last opening (the direction of the flux is especially important). A closing strategy that neglects the transformer residual flux will lead to anything but optimum conditions. However, even in this case, the worst conditions that can occur with conventional circuit-breakers can be avoided by using a synchronous circuit-breaker.

In the worst case, inrush currents are of the order of 8–15 times the transformer full-load current rating [2]. *Table 2* shows the reduction in inrush current obtained with controlled closing, the data being based on modelling of a specific transformer behaviour. A comparable current reduction is expected for other winding configurations and ratings.

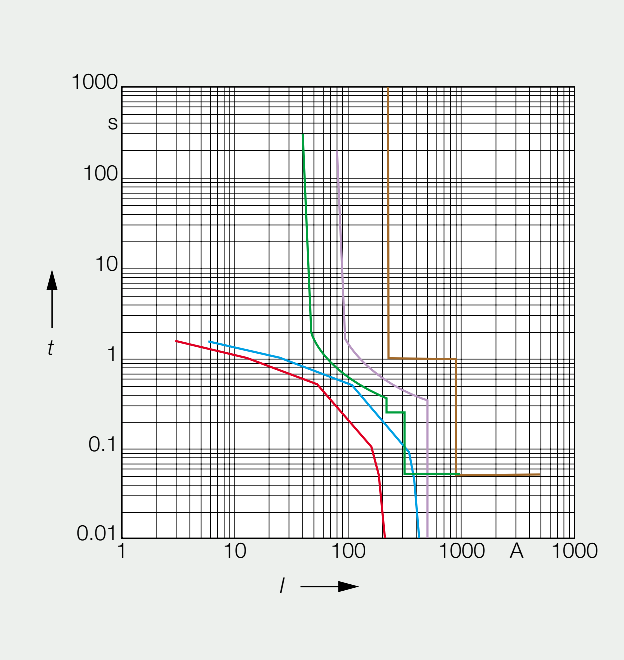
Better protection and selectivity

The reduction of transformer inrush currents to negligible values allows wider margins when selecting the protection relay curves and avoids unnecessary trips. Other benefits are that it allows concurrent energization of several transformers, together with small power generators, and eliminates a typical



Switching capacitor bank C1 causes a typical overvoltage of 1.8 pu at C1 (blue curve), and more than 3.5 pu at C2 (red curve) due to magnification. **10**

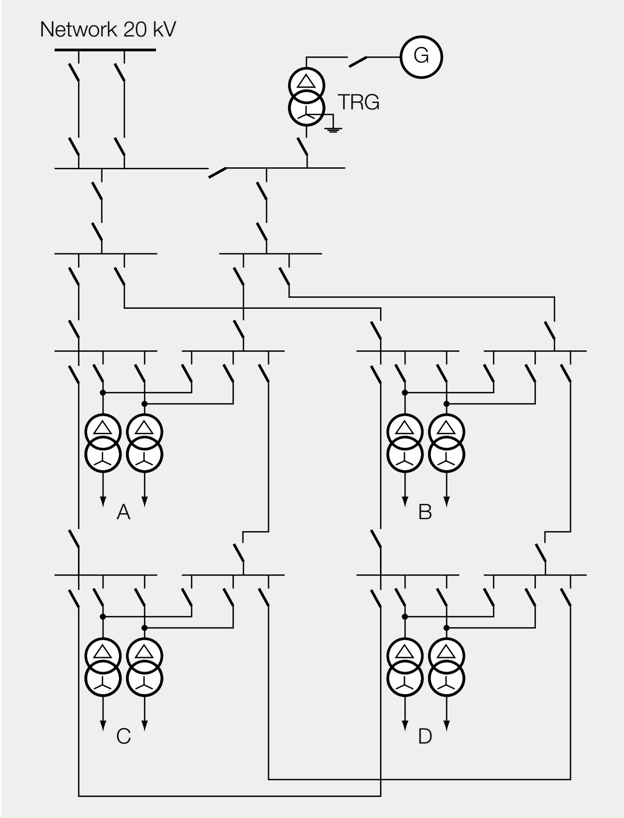
U Voltage *t Time*



Time-current protection diagram in which two transformer inrush curves intersect with the circuit-breaker curve **11**

Red	*Inrush current, one transformer*
Blue	*Inrush current, two transformers*
Green	*Breaker B*
Pink	*Breaker A*
Brown	*Utility protection curve*

I *Current*
t *Time*



Schematic of the energy network at Fiumicino (Rome) airport **12**

A, B, C, D	*Transformers A, B, C, D*
G	*Standby generator*
TRG	*Generator transformer*

cause of fuse aging. This considerably improves power availability.

In a typical time-current diagram of protection coordination **11**, selectivity is ensured when the curves of the equipment on the load side are located below those of the equipment on the supply side. The limits are given in the upper part by the tripping curve of the equipment in the network on the load side of the plant, and in the lower part by the inrush curve of the transformers.

These often stringent limits result in a curve 'crush', preventing suitable tolerances from being applied to the thresholds and risking possible untimely tripping. This often prevents the concurrent energization of several transformers in parallel.

Example of concurrent energization made possible by SCBs

At Fiumicino (Rome) airport only one transformer can be energized at a time under emergency conditions **12**. This is because of the time interval that is needed until energization of the following transformer in order to avoid protection tripping of the generator. The result is a long and complex

Table 2
Reduction of transformer inrush currents (peak value) in pu when SCB is used

Case	Switching device	Inrush [pu]
Residual flux present; worst case	Circuit-breaker	up to 7.5
Residual flux present; closing strategy disregards value	SCB	up to 3.0
Residual flux present; optimal closing strategy	SCB	0.05

SCB *Synchronous circuit-breaker*

procedure for energizing the emergency loads after loss of the network supply. Use of synchronous circuit-breakers shifts the inrush to the left in the time-current protection diagram, allowing easier and more reliable protection coordination as well as concurrent energization of all the emergency loads. Significantly reduced downtime is the result.

Methods of reducing switching transients

The most effective way to reduce switching overvoltages is to use appropriate switching equipment. The protection of sensitive equipment by means of surge arresters, chokes or higher insulating levels is expensive and not always effective. Alternative, traditional methods designed to avoid switching transients are compared in *Table 1*. A synchronous circuit-breaker offers a simpler, more cost-effective solution than, for example, fixed or pre-insertion inductors or pre-insertion resistors [5].

The SCB allows effective reduction of the current as well as the voltage transients. Both opening and closing synchronous operation can be handled by configuring the software of the control electronics to suit the circuit-breaker installation. The SCB is also much more flexible in load operation.

Summary

The described SCB is designed as a turnkey device for full integration in medium-voltage switchgear, thereby providing synchronous functionality at the distribution level. *Table 3* shows the ratings of the first SCBs scheduled to be launched.

ABB synchronous circuit-breakers are multi-purpose, flexible devices with fully configurable software. They extend the range of synchronous operation from capacitor bank switching to all distribution circuit-breaker applications, including the synchronous interruption of short-circuit currents.

The SCBs offer flexible solutions that can be used in all types of networks, eg isolated networks and compensated power systems with an extinguishing arc coil, a neutral connected to the ground by means of a resistor, and a strongly grounded neutral.

Synchronous circuit-breakers offer high quality and reliability over their expected service life. In addition, maintenance requirements are reduced, availability and service continuity are improved, and a cost-saving is possible in the increasing number of applications in which power quality is important.

Table 3
Available ratings in first step

SCB	Rated voltage	Rated current	Breaking current
SF_6	12 kV	630 / 1250 A	20-25-31.5 kA
	17.5 kV	630 / 1250 A	16-20-25 kA
	24 kV	630 / 1250 A	16-20-25 kA
Vacuum	12 kV	630 / 1250 A	20-25-31.5 kA
	17.5 kV	630 / 1250 A	16-20-25 kA
	24 kV	630 / 1250 A	16-20-25 kA

SCB *Synchronous circuit-breaker*

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Authors

Carlo Cereda
ABB SACE TMS
Via Friuli, 4
IT-24044 Dalmine, Italy
Telefax: +39 035 395 869
E-mail: carlo.cereda@itscb.mail.abb.it

Carlo Gemme
ABB Ricerca SpA
Corporate Research Italy
Viale Edison, 50
IT-20099 Sesto San Giovanni, Italy
Telefax: +39 02 26232 188
E-mail: carlo.gemme@itric.mail.abb.com

Christian Reuber
ABB Calor Emag Mittelspannung GmbH
Oberhausener Strasse 33
DE-40472 Ratingen, Germany
Telefax: +49 2102 12 1808 1544
E-mail: christian.reuber@de.abb.com

Measurements prove high performance of first CB/A axial surface-type steam condenser

Special demands are made on the steam condenser and vacuum deaeration system designed and built by ABB Alstom Power licensee, Evans Deakin Engineering Pty Ltd of Australia, for a 180-MW combined cycle facility near Sydney. In addition to supplying electrical power to the grid, the plant also supplies process steam in large quantities to local industry. A comprehensive test programme has shown that the CB/A axial surface-type steam condenser and the deaeration system easily meet the high performance requirements under the test conditions, while also satisfying environmental needs. Evaluation of the extensive measurements has verified ABB Alstom Power's calculation methods and provided data that will serve as a reliable basis for further development work.

ABB Alstom Power licensee, Evans Deakin Engineering Pty Ltd of Australia, was responsible for designing, building and installing the steam condenser and vacuum deaeration system for the 180-MW combined cycle power station at the Smithfield Energy Facility, 50 km south-west of Sydney. The power station has three gas turbines and one steam turbine for electricity generation, and also supplies up to 50 % of the live-steam mass flow as process steam to a paper factory, making it a significant contributor to the local energy market. Natural gas is used to fire the gas turbines. The steam turbine receives live steam from the gas turbine waste-heat boilers. The steam condenser, a CB/A axial surface-type unit developed by ABB Alstom Power, operates with cooling towers.

Because of the large quantities of process steam involved, the systems installed to condition and, in particular, deaerate the make-up water have to be flexible as well as very efficient.

The CB/A condenser is the result of further development of the proven underfloor CB condensers and is the first axial surface condenser of this type to be built world-wide. The dominating feature of the new design is that the steam flows horizontally in the direction of the turbine axis as it passes from the LP exhaust to the bundle area.

Dr. Peter Baumann
Walter Novak
ABB ALSTOM POWER

Felix Kuhn
Evans Deakin Engineering Pty Ltd

During commissioning ABB Alstom Power teamed up with Evans Deakin, the EPC contractor NEPCO-Transfield Joint Venture Company (NTJV) formed by the engineering companies TRANSFIELD Ltd of Australia and Zurn Nepco of Redmond, USA, and the client and owner of the Smithfield Energy Facility, Sithe Energies Australia Pty Ltd, to investigate the performance of the condenser and vacuum deaeration system. Other goals of the extensive test programme were to obtain detailed data as a basis for further development work and to check ABB Alstom Power's in-house design rules and methods of calculation.

Steam condenser and vacuum deaeration system

The purpose of the condenser and deaerator system installed at the Smithfield Energy Facility **1** is to condense the working steam leaving the steam turbine and to extract the oxygen from the make-up water and the main condensate.

Steam condenser

Due to its effect on the backpressure of the LP steam turbine, the performance of the condenser has a decisive influence on the efficiency of the entire plant, and therefore on the generator output.

Via the cooling water the condenser is also a link to the environment. Besides fulfilling the requirements of the power plant it therefore also has to satisfy environmental needs. This important requirement is satisfied by ABB Alstom Power condensers in all areas – from the thermal design to the fabrication and operation – and is guaranteed by ISO 14001 certification [1].

The type CB/A surface condenser ('A' stands for 'axial') **2** (*Table 1*) represents

CB/A steam condenser in the 180-MW combined cycle power station of Smithfield Energy Facility, Australia **1**

the most recent result of ongoing development of the CB condenser, which was introduced to the market in 1989. Further development of the CB condensers for axial and lateral turbine exhausts was based on field data from 50 condensers in underfloor arrangement operating worldwide. The thermal load range of this condenser type is 10 to 250 MW [2].

Besides their main function, which is to act as a heat-sink, steam turbine condensers are increasingly gaining recognition as an important part of the vacuum deaeration system in plants in which large quantities of make-up water are used. In the past 2 % of the live-steam was considered to be a characteristic value for the make-up water, which usually had to be added to the system discontinuously via the condenser. Today, make-up water may constitute as much as 50 % of the turbine live-steam mass flow rate and has to be added continuously, as in complex combined cycle systems with large-scale process steam extraction.

Vacuum deaeration system

The vacuum deaeration system used in the Smithfield Energy Facility is reliable under rigorous operating conditions and guarantees a residual oxygen content of less than 7 ppb in the condensate leaving the hotwell even under severe make-up conditions in which the make-up water flow to the condenser constitutes up to 50 % of the turbine live-steam mass flow rate.

Table 1
Main design parameters of the condenser

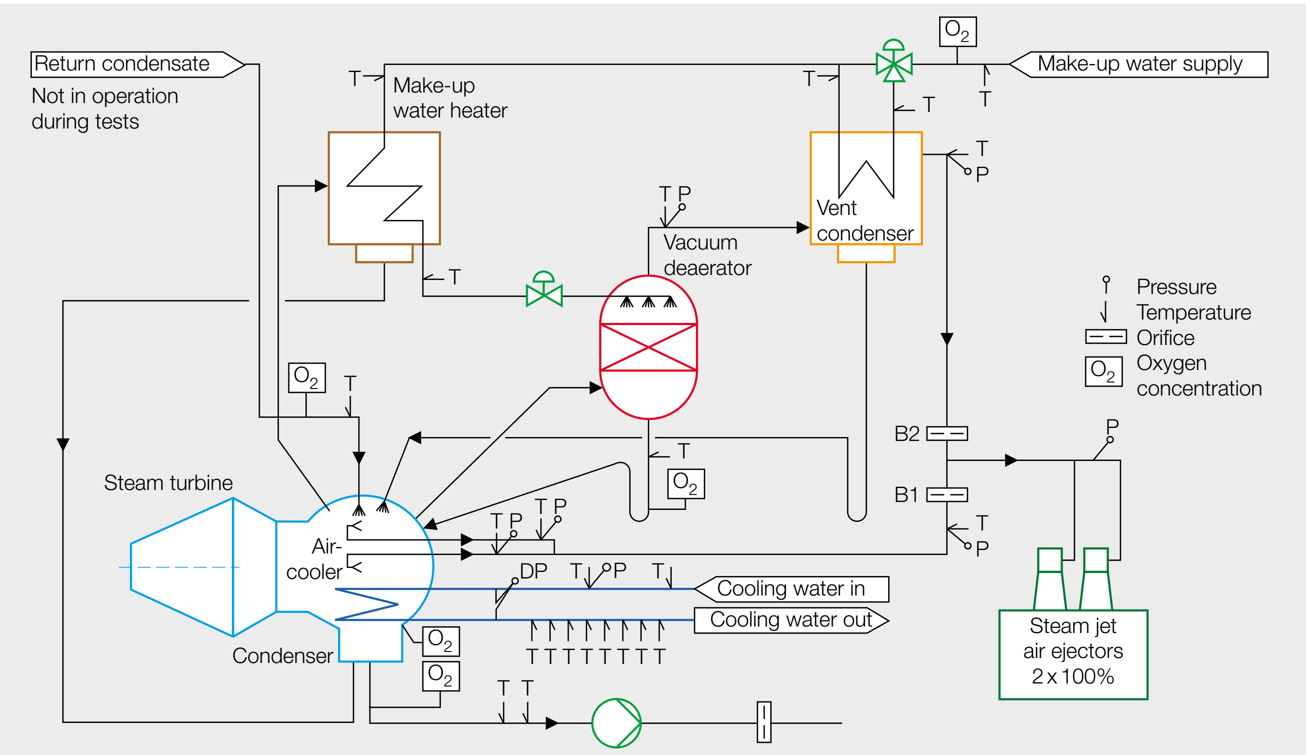
Condenser type	CB/A-108-2x3164/25,4/07
Number of passes	2
Water box type	Non-divided
Tube material	Stainless steel
Tube sheet material	Stainless steel
Tube/tube sheet connection	Expanded
Tube length	10.89 m
Cooling area	5458 m^2
Heat load	92.25 MW
Live-steam mass flow rate	45.0 kg/s
Condenser pressure	0.048 bar
Cooling-water inlet temperature	22 °C
Cooling-water pressure drop	0.543 bar

CB/A condenser for Smithfield Energy Facility being manufactured at Evans Deakin's workshop **2**

As **3** shows, two 100% steam jet air ejectors are provided (one nominally in operation) to vent the condenser and the vacuum deaeration system. Orifices B1 and B2 determine how much of the venting capacity of the ejectors is assigned to the condenser and how much to the deaerator system.

Thorough venting of the vacuum deaerator is ensured by passing some of the make-up water through the vent condenser. The make-up water is subsequently pre-heated in the make-up water heater almost to saturation temperature at the prevailing condenser pressure, whereby the top section of the packing, where deaeration tends to be ineffective, is minimized. This ensures that the vacuum deaerator operates with the highest efficiency over the full packing height with comparatively small-diameter packing. The section of the condenser shell that receives the make-up water from the vacuum deaerator is designed as a so-called 'fall film' deaerator. In this design, the make-up water is distributed in the form of a film over the full length of the condenser shell's back-wall, thereby providing further intensive contact with fresh turbine exhaust steam for effective final deaeration of the make-up water.

Schematic of measurement system installed for the condensing and vacuum deaeration system in Smithfield **3**



Both the vent condenser and the make-up water heater are designed as ABB Alstom Power shell and tube heat-exchangers.

Determination of characteristic parameters

The condenser performance was determined experimentally using test instrumentation based on ASME PTC 12.2 and the relevant internal guidelines. The scope covered by the tests exceeded the requirements given in ASME PTC 12.2 for such measurements.

The following plant parameters were determined:

Heat load to condenser

This was determined by means of a plant energy balance. Additional relevant data were obtained from the plant's permanent data acquisition system.

Cooling-water flow rate

This was determined via the condenser energy balance with the aid of the determined heat load to the condenser.

Global cooling-water temperature rise

The overall rise in the temperature of the cooling water was measured with medium wetted Pt 100 sensors, inserted in special support sleeves. Two measuring points were positioned at the cooling-water inlet, and another eight inserted radially and distributed on the circumference around the cooling-water outlet line.

Local cooling-water temperature rise

The cooling-water temperature rise was measured locally at the first and second pass of selected individual cooling-water tubes. The temperature sensors were positioned across the entire tube area of the first pass cooling-water outlet and the second pass cooling-water inlet and outlet. The cooling-water temperature was measured at a total of 108 points and allowed the temperature rise to be determined along individual tubes. Thermocouples were used as temperature sensors, the cooling-water inlet temperature serving as reference. As a result of these measurements, cooling-water temperature rise profiles were obtained for the entire areas of the tubes. These provided important information about the condensation behaviour of the condenser.

Condenser pressure/temperature

On the steam side, the condenser was fully fitted with so-called combined sensors for simultaneous measurement of pressure and temperature. To ensure correct pressure measurement, all pressure tapping points were equipped with ASME guide plates. The measurement was carried out in two planes in the exhaust flow path from the turbine to the condenser, namely in the cylindrical turbine exhaust nozzle (12 measuring points) and approximately 300 mm before the first tube row in the condenser tube areas (18 measuring points).

The use of combined sensors and the number that were fitted easily exceeds the requirements stipulated for this area in ASME PTC 12.2.

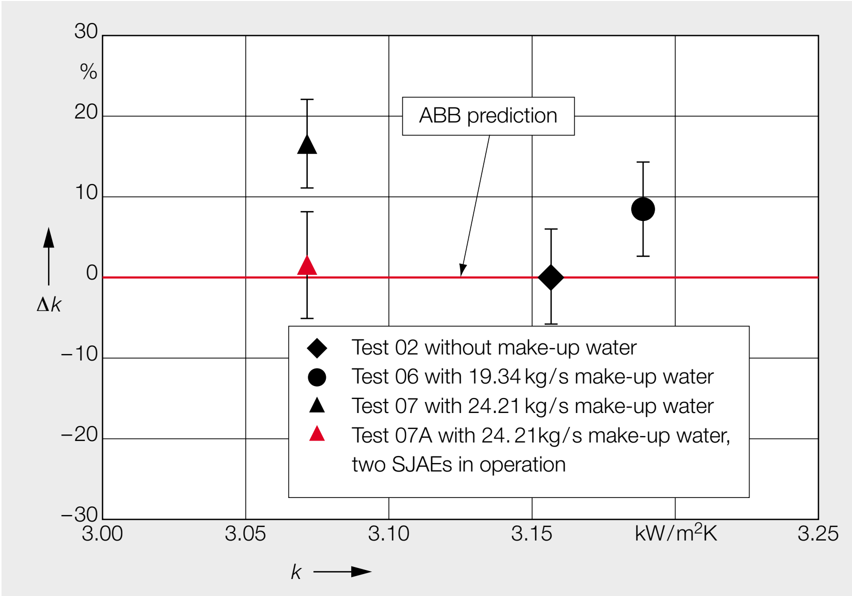
The relatively narrow and complex steam path geometry results in very complex flow and pressure conditions. An extensive installation was therefore necessary to obtain condenser pressure data accurate enough to be used as a basis for further development work.

Vacuum drop test

The steam jet air ejectors were isolated and the pressure rise in the condenser and vacuum deaeration system was recorded with respect to time. This test provided information about the air-tightness of all the evacuated systems, including the vacuum deaeration system, condenser and low-pressure turbine.

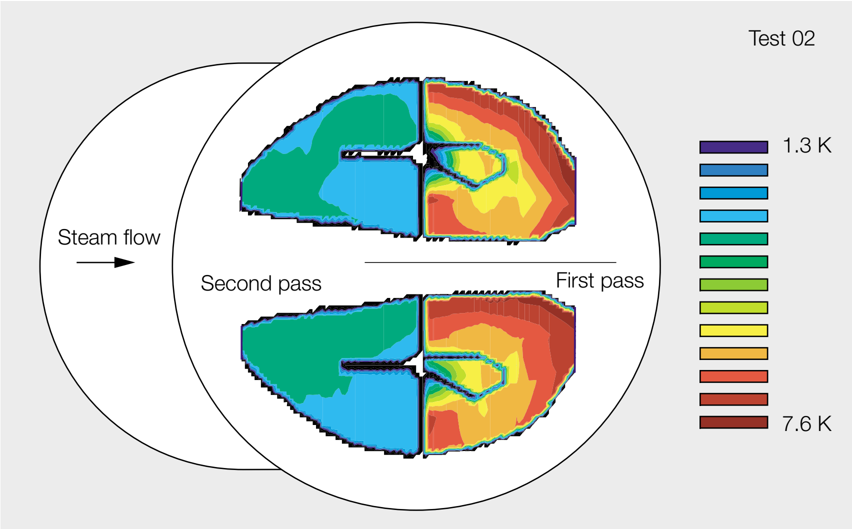
Condensate temperature

Using two Pt 100 sensors, the condensate temperature was measured in the condensate extraction pipe downstream of the



Deviation of the measured heat transfer coefficient from values predicted by in-house design calculations **4**

Δk Deviation of heat transfer coefficient, k



Measured cooling-water temperature rise for test 02 (without make-up water) **5**

Thermal load: 112.7 MW; make-up water: 0.0 kg/s

hotwell but upstream of the main condensate extraction pumps.

Cooling-water pressure drop

The pressure drop across the condenser on the cooling-water side was measured by means of a differential pressure sensor. Prior to actual measurement, it was assured via the water box vent lines that the water boxes had been fully vented. The measuring points in the cooling water nozzles were approximately 0.5 m from the respective water boxes.

Oxygen content in condensate

These measurements were carried out with instruments from the company *Orbisphere*. High diffusion tight plastic hoses and high-quality stainless steel lines and fittings were used for the extraction pipes. A variable-speed extraction pump was used to adjust the extraction flow rate to the value specified for the oxygen analyzers.

Cleanliness factor

The condenser was inspected on the steam- as well as on the cooling-water side. The inspections showed it to be technically clean, with the cooling-water side in particular showing no signs of contamination.

A cleanliness factor of 0.85 was therefore used for the evaluation of the results. This value is usual for such a plant without an automatic tube cleaning system, and also corresponds to the design value.

Table 2
Standard qualification of ABB Alstom Power test instrumentation

Instrument type	*Measurement uncertainty*
Resistance thermometers	± 0.03 K
Thermocouples, temperature difference	± 0.02 K
Turbine exhaust pressure transducer	± 0.25 mbar
Difference pressure transducers	± 0.14%
Data acquisition system	± 0.03%

Test instrumentation and additional data

All the measuring points with the temporarily installed high-precision sensors are shown in **3**. (To keep the diagram simple, some of the measuring points used for the condenser assessment are not shown.) All other data required for the energy and mass flow balances were derived from plant instrument readings.

Data recording

The ABB Alstom Power Universal Data Acquisition System, UNIDAS II [4], was used as it permits automatic scanning and recording, and allows even large quantities of data to be evaluated with high accuracy under field test conditions (*Table 2*). The system is specially designed for temporary use in power stations. Highly accurate results are ensured by the transmitters, which are an integral part of the recording and evaluation system and are freshly calibrated each time before use. The system meets the requirements of all the relevant international standards for guarantee tests (ASME, DIN, VGB, BS, ISO, IEEE, IEC, etc).

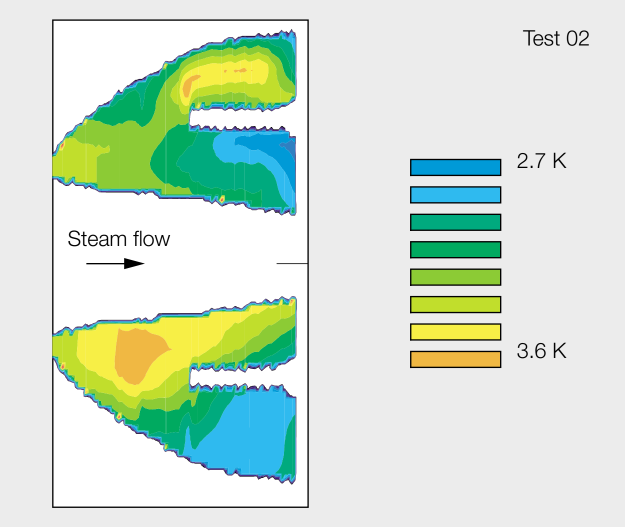
Data evaluation

The calculated 95 % confidence interval for the measured values and error propagation (eg, when determining the global heat transfer coefficient) verifies that UNIDAS II easily satisfies the accuracy requirements of this benchmark test programme.

Test results

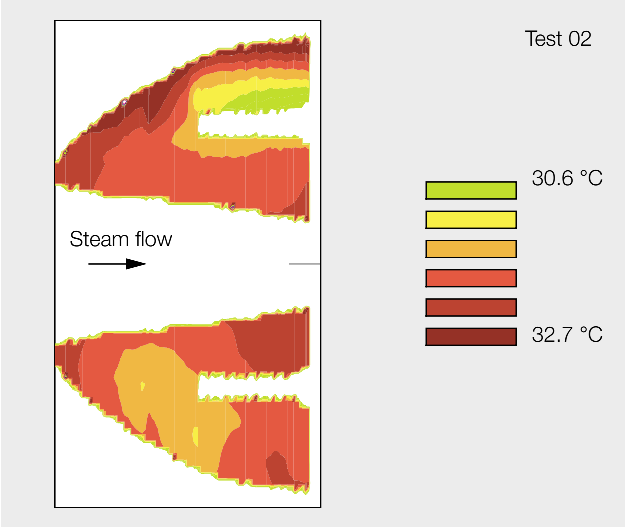
Condenser pressure and heat transfer coefficient

The condenser pressure at the plane immediately before the tube bundles was used to determine the heat transfer coefficient, the so-called *k*-value. This is in agreement with HEI [5] ASME PTC 12.2 and the ABB guidelines.



Cooling-water temperature rise in second pass (test 02), shown with a higher resolution 6

Thermal load: 112.7 MW; make-up water: 0.0 kg/s



Cooling-water inlet temperature in second pass (test 02) 7

Thermal load: 112.7 MW; make-up water: 0.0 kg/s

To evaluate the condenser pressure in this plane all the measuring points were used at which the measured pressure did not deviate by more than 0.002 bar from the calculated saturation pressure at the corresponding measured temperature. This was necessary to ensure that only pressure readings that are not falsified by condensate accumulation in the instrument lines are used for the evaluation. The permitted maximum pressure difference, ΔP_{max}, is given by:

$$\Delta P_{max} = P_{exp} - P_{sat}(T_{exp}) \leq \pm 0.002 \text{ bar}$$

Where P_{exp} is the experimental pressure and P_{sat} the saturation pressure at the experimental temperature, T_{exp}.

The condenser pressure now being known, an experimental heat transfer coefficient was determined and compared with the ABB Alstom Power design calculations.

Table 3 shows the thermal load and amount of make-up water for four representative tests, designated 02, 06, 07 and 07A. In 4, which shows how the measured data deviate from the calculated values, good agreement can be seen for the test without make-up water (02). Also worth noting is the difference in the deviation for tests 06 and 07, ie for operation with large quantities of make-up water and one steam jet air ejector (SJAE) in operation. As soon as the second SJAE is put into operation, the condenser pressure improves considerably (test 07A).

These results indicate that the higher than expected air in-leakage prevailing during the test programme (approximately three times the design air in-leakage rate) did to some extent impair the heat transfer in the tests with large quantities of make-up water, and particularly during test 07. However, in spite of this higher air in-leakage the tube bundle venting remained effective and the oxygen readings for the condensate leaving the hotwell were still better than the guaranteed value of 7 ppb. This was true even for test 07 with the largest quantity of make-up water.

Local cooling-water temperature rise in individual cooling water tubes

Operation without make-up water

5 shows the cooling-water temperature rise along the first and second pass for test 02 (without make-up water). Also clearly

Table 3
Thermal load and make-up water for four representative tests

Test	Thermal load [MW]	Make-up water [kg/s]	Make-up water [% of main steam flow]	No of SJAEs in operation
02	112.7	0.0	0.0	one
06	100.2	19.34	29.5	one
07	92.9	24.21	37.3	one
07A	92.9	24.21	37.3	two

seen is the steam penetration in the first pass of the tube bundle and the local influence of the condensate flow in the bundle on condenser performance.

In the top and bottom bundles of the first pass the steam and condensate flows are in the same direction at the upper periphery. The result is a typical 'onion shell' pattern describing the condensation performance along the steam flow path.

In the lower bundle halves the steam and condensate flow in opposite directions. It can be clearly seen where the condensation capacity is reduced due to cascading condensate or increased to nearly full condensation capacity due to the shielding effect of the air-cooler plates. The air-cooler tubes also show a very high condensation capacity, demonstrating the perfect venting of the bundle. The nearly identical behaviour of the upper and lower bundles of the first pass can be explained by the condensate baffle plate between the bundles.

In the second pass the profile of the cooling-water temperature rise tends to be homogeneous, the maximum difference in temperature rise being 0.9 K. A condensate baffle between the bundles is not necessary here because of the relatively small quantity of condensate.

A more detailed look at the second pass

A closer look at the second pass of test 02, using a higher resolution for the cooling-water temperature rise, is shown in **6**. The flat pattern is due to the combination of three effects:

- Flooding of bundle areas due to cascading condensate
- Cooling-water temperature profile at inlet to second pass
- Different steam admission conditions
  – steam/condensate in parallel flow
  – steam/condensate in counter flow

It can be assumed that all the cooling-water tubes in all bundle areas operate with the same quantity of cooling water.

A common characteristic of both the upper and lower bundle of the second pass is that the cooling-water temperature rise is smallest in the right-hand, lower bundle section. This is caused on the one hand by a relatively high cooling-water inlet temperature **7** and on the other by flooding of this bundle area, which increases gradually due to condensate cascading downwards. Furthermore, the steam entering the bundle flows in a counter direction to the condensate flowing down to the bottom.

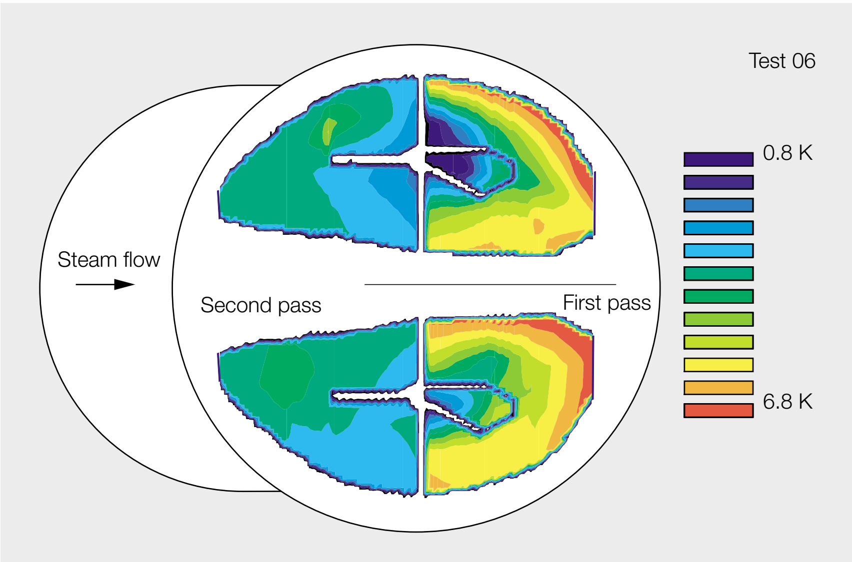
6 also shows stratification of the cooling-water temperature rise and an isolated maximum in the lower bundle. This would not normally be expected with such a shape. The stratification can also be explained by the flooding of the bundle by condensate cascading from above. The fact that the maximum temperature rise in the lower bundle represents an 'island' can be explained by the distribution of the cooling-water inlet temperature **7**. As warm water approaches the upper periphery of the lower bundle, the rise in the cooling-water temperature there is smaller than it is inside the bundle. Although the cooling-water inlet temperature in the middle section of the lower bundle is lower than at the upper periphery, it rises much less than at the upper periphery. This can also be explained by greater bundle flooding and poorer steam admission at the lower bundle periphery due to cascading condensate.

It is mainly in the area where flooding with condensate has only a small influence that the condensation capacity is determined by the local cooling-water inlet temperature. This is confirmed by the results of measurements carried out on the upper bundle of the second pass.

7 shows two interesting phenomena: first, a minimum cooling-water inlet temperature prevails in the top section of the upper bundle above the inner bundle steam lane; second, the cooling water in the reversing chamber is stratified such that there is a significant maximum cooling-water inlet temperature at the upper bundle periphery. Although this upper bundle periphery is well-charged with steam, no significant flooding by foreign condensate is evident. In spite of the parallel steam and condensate flows, the rise in cooling-water temperature **6** is smaller than in the bun-

Measured cooling-water temperature rise for test 06 (with make-up water) **8**

Thermal load: 100.2 MW; make-up water: 19.34 kg/s



dle area with a lower cooling-water inlet temperature.

ABB Alstom Power design calculations for condensers are based on physical models which take account of the effects described above. This explains the close agreement between the calculated and measured values in tests 02 and 07A.

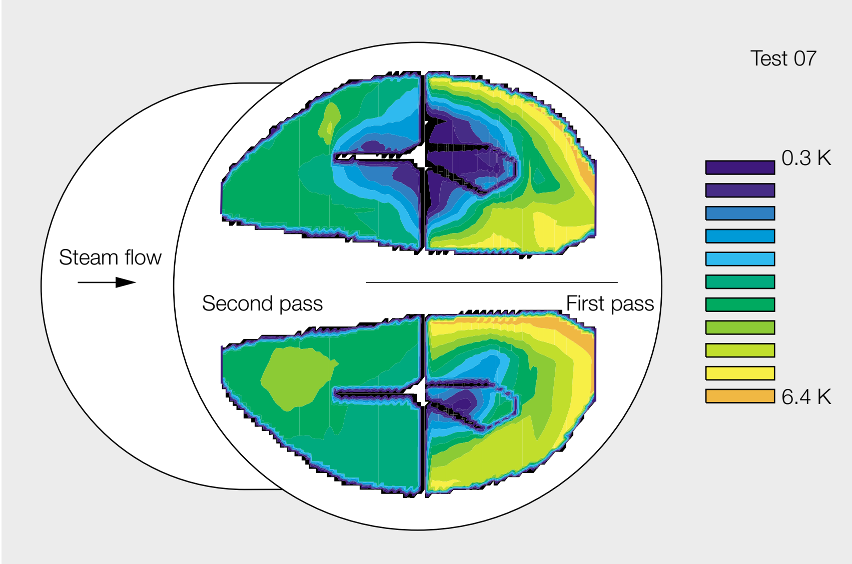
Operation with make-up water

8 shows the distribution of the cooling-water temperature rise for test 06, in which 29.5 % of the main steam flow rate is make-up water. The deterioration in the cooling-water temperature rise profile, indicating impairment of the condenser heat transfer capacity in the air-cooler area, is clearly visible.

A further increase in the quantity of make-up water results in the conditions shown in **9** for test 07. Here, nearly 40 % of the quantity of live steam is supplied as make-up water. Comparison of test 07 and test 06 shows clearly the impaired condensation capacity due to air blanketing in the air-cooler area, with an obvious center in this area, indicating that the total non-condensable load exceeded the extraction capacity of one steam jet air ejector unit under the test conditions.

Hence, increasing the venting capacity or limiting the air in-leakage to the condenser to the design value should result in a significant improvement in condenser performance. This is supported by the fact that the area with the lowest cooling-water temperature rise is located, and also remains, in the air-cooler section. Next to this area a cooling-water profile forms which is always directed towards the air cooler. This is consistent with a pressure profile on the steam side, which ensures that the venting flow is always directed towards the air cooler. The formation of isolated zones with no cooling-water temperature rise outside the air-cooler area is prevented by the ABB Alstom Power tube bundle design. A higher venting capacity or the limitation of air in-leakage will therefore always result in an improvement in the condenser performance under high non-condensable load conditions, as evident in test 06 and test 07. This has been clearly demonstrated by changing from operation with one to operation with two steam jet air ejectors (tests 07 and 07A).

The condenser pressure characteristic for the cases with one and two SJAEs in operation is shown in **10**. Similarly, the local cooling-water temperature rise is different for these two cases. The situation shown in **9**, which reflects the local cooling-water temperature rise with one SJAE in operation, is used as the starting point. The mode with two SJAEs in operation passes through a transient phase (9:47 to



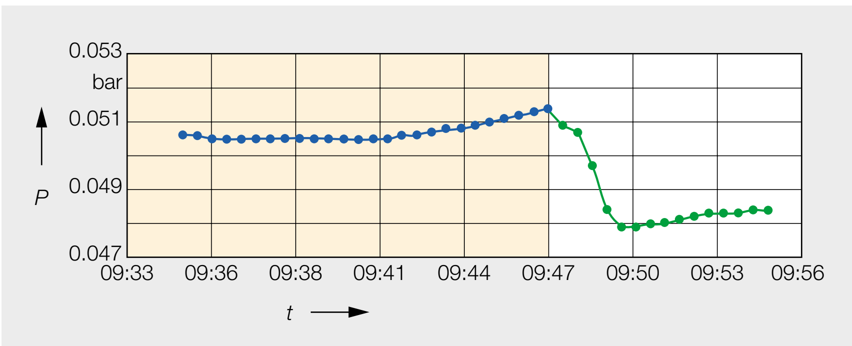
Measured cooling-water temperature rise for test 07 (with make-up water) **9**

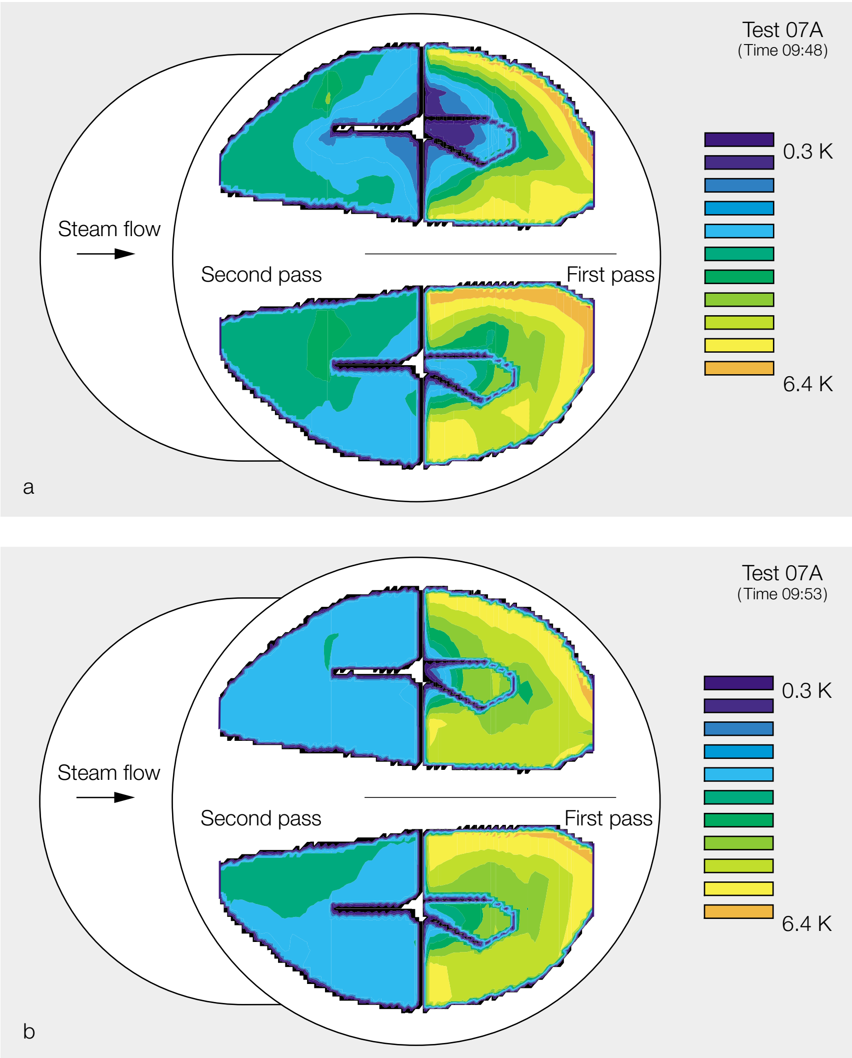
Thermal load: 92.9 MW; make-up water: 24.21 kg/s

Condenser pressure readings during test with one and two steam jet air ejectors in operation **10**

Test 07; 1 SJAE in operation
Test 07A; 2 SJAEs in operation
P Pressure
t Time

Make-up water: 24.21 kg/s





Cooling-water temperature rise for two SJAEs in operation (test 07A), measured during the transient phase (a) and steady-state phase (b) **11**

Thermal load: 92.9 MW; make-up water: 24.21 kg/s

9:49) **11a**, followed by steady-state conditions **11b**. The trend is clearly towards a perfectly functioning condenser, the reason for the significant improvement in performance being in this case the increased venting capacity, which effects the rapid elimination of the air blanketing in the air-cooler area.

Oxygen content in the vacuum deaeration and main condensate system

The guaranteed value of the oxygen content in the condensate from the hotwell is 7 ppb. All the tests verified, and **12** shows, that the oxygen content in the condensate line upstream of the main condensate pumps remains well below this value. Even with the largest quantities of make-up water (test 07), the oxygen content in the condensate remains below 3.5 ppb, being clearly due to the significant contribution made by the fall-film deaerator.

Condensate subcooling

Condensate subcooling, T_{cs}, is defined as the difference between the condenser temperature (saturation temperature at condenser pressure), T_c, and the condensate temperature in the main condensate line, T_{ch}:

$$T_{cs} = T_c - T_{ch}$$

As **13** shows, condensate subcooling is always negative, regardless of the operating conditions. This fact, which has also been verified by other tests, confirms the excellent regenerative properties of this condenser concept and underlines the considerable contribution ABB Alstom Power condensers make to minimizing the exergetic losses of the overall plant.

Vacuum decay

By measuring the condenser vacuum decay rate it is possible to determine the air in-leakage into all parts of the system at below-atmospheric pressures.

A vacuum decay rate of 6 mbar/min was measured, indicating that the air in-leakage into the system during the tests was approximately three times the design air in-leakage rate. As verified by tests 06 and 07, the excessive air in-leakage had

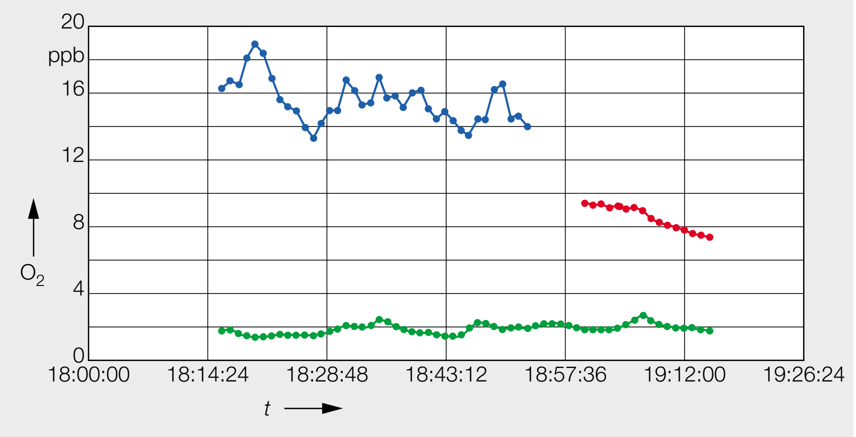
Table 4
Cooling-water pressure loss, Δp

Test no	Thermal load [MW]	Make-up water [kg/s]	Δp_e experiment [bar]	Δp_c calculated [bar]	$\frac{\Delta p_e - \Delta p_c}{\Delta p_e}$ [%]
Test 02	112.69	0.000	0.531	0.510	4.100
Test 06	100.21	19.340	0.534	0.554	–3.600
Test 07	92.9	24.210	0.540	0.535	0.900

an adverse effect on the heat transfer at the condenser tubes, especially with high make-up water flow rates and only one SJAE in operation.

Pressure loss on the cooling-water side

Table 4 shows the good agreement of the test results with ABB Alstom Power's design calculations. The accuracy of the measurements of the pressure loss on the cooling-water side also made it possible to verify the rate of flow of the cooling water supplied by the cooling-water pumps.



Oxygen content in condensate (test 06) **12**

Thermal load: 100.2 MW; make-up water: 19.34 kg/s

Condensate pipe
After falling film deaerator
After deaerator

O_2 *Oxygen content*
t *Time*

Summary of test results

The measurements show that the performance of the condenser and vacuum deaeration system easily meets the customer's requirements under the test conditions. It can also be clearly seen that the outstanding regenerative characteristic and the deaerating capability of the ABB Alstom Power tube bundle is in no way impaired by higher than expected air in-leakage rates, even with high make-up water mass flows. As the evaluation shows, the experimental findings reflect the reliability of the in-house calculation methods for CB steam condensers in axial arrangement.

The success of the comprehensive measurement programme and its completion within a tight time schedule can be attributed to a large extent to the excellent co-operation between all parties involved.

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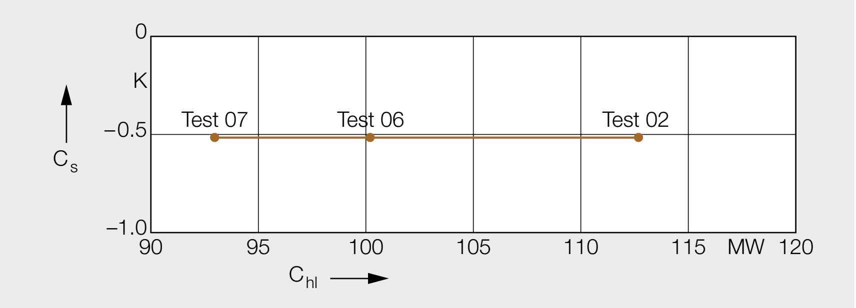


Condensate subcooling (tests 02, 06, 07) **13**

C_s *Condensate subcooling*

C_{hl} *Condenser heat load*

Authors

Dr. Peter Baumann
Walter Novak
ABB ALSTOM POWER
CH-5401 Baden, Switzerland
Telefax: +41 56 205 5959
E-mail: peter.baumann@ch.abb.com
E-mail: walter.novak@ch.abb.com

Felix Kuhn
Evans Deakin Engineering Pty Ltd
12 Boundary Street
South Brisbane, QLD 4101, Australia
E-mail: fkuhn@ede.com.au

EMC and the ABB Group in the next millennium

Electromagnetic compatibility (EMC) is the property of electrical or electronic equipment that enables it to operate reliably in its electromagnetic environment without interfering with the operation of other equipment, especially third-party apparatus, such as radios, televisions and mobile communication systems. Today, EMC is an established scientific discipline based on mathematics, physics and theoretical electrical engineering. ABB is able to satisfy not only the legal stipulations, which should be considered as the minimum level of EMC required, but also the most demanding requirements in this extremely challenging field.

Within Europe, electromagnetic compatibility (EMC) is regulated by the EMC Directive and national laws. Whereas the EMC Directive covers and regulates the protective requirements, the technical requirements are always regulated by what are known as the 'European Harmonized Standards'. The legal requirements of the EMC Directive have to be considered as a minimum, as they do not always meet the full requirements of the product end-users.

As far as the EMC Directive is concerned, the biggest challenge in the future will most likely involve installations 1 and IT (Information Technology) equipment. In the case of the installations the main issue will be: who has legal responsibility for their EMC compliance. This is because EMC properties are widely perceived as being the joint responsibility of the manufacturers and assemblers. The second concern has to do with the widespread use of IT equipment, including personal computers, and the fact that new generations are developed and brought to market at very short intervals. Besides having an extremely short technological lifetime, this equipment is usually designed for domestic applications that bear no resemblance to most industrial environments.

Future products

The ABB Group supplies industry with a huge range of components, finished products, systems and installations. Designing electronic products to operate in an industrial environment largely involves mastering the art of making them electromagnetically compatible. The most difficult task the designer faces in connection with EMC is identifying differences between the ideal and actual properties of the electrical connections, the passive components and the active components. This is necessary, however, for correct computer-based modelling, simulation, calculation and trouble-shooting.

Industry is constantly demanding new technology. Usually, this is based on modern microprocessor systems and their peripherals. Industrial equipment will continue to feature high-performance analogue circuits and more and more functions for high-speed communications will be included in the design. New technology introduced to the market in the future will offer a previously unimaginable potential for increasing production and performance, while at the same time reducing costs, lessening environmental impact and improving quality.

Every manufacturer introducing new technology has to deal with two groups of people: one which looks upon it with enthusiasm and one which is sceptical.

Manufacturers and suppliers of new technology have both a responsibility and an obligation not to disappoint the enthusiasts, yet at the same time must convince the sceptics that the new technology has come to stay and really does 'deliver' the promised advantages.

Presumably there is no manufacturer who, if he wants to survive, will not strive to ensure that the equipment he is offering will live up to his claims. And it can also safely be assumed that every manufacturer will ensure that his product works properly in the development department and laboratory.

However, it has to be asked whether this is enough to guarantee trouble-free operation and satisfied customers? The answer is a simple yes, providing the sources of interference existing in the industries for which the product is intended are taken into account, and the manufacturer checks this by performing EMC tests relevant to the intended environment and application.

When this is done, and the equipment comes up to all expectations, it will be an easy matter to convince the pessimists that their doubts are unfounded.

The conclusion to be drawn from this is that the manufacturing company has to pursue a policy of ensuring that every circuit-board, product, system and installation satisfies the requirements for industrial use, and does it with generous margins. This must be

Dr. Sten Benda
ABB EMC Certification AB

verified by means of EMC tests. A policy of designing all products so that they are free of interference is crucial to a company's success, and the lack of such a commitment could spell disaster for the customer or supplier, or both.

Circuit theory

Electronics used in early control and supervision systems contained very simple electromechanical components and electron tubes. Such equipment was slow, and the interference signals that posed a risk were only in the low-frequency ranges. The philosophy adopted for the suppression of disturbances could be kept very simple and it was enough to use circuit theory based on Ohm's and Kirchhoff's laws.

Today, it is still common for theoretical EMC analyses to be based on electric circuit theory. However, such theory uses as its platform many scientific abstractions which more or less ignore the relevant facts. Also, the circuit parameters which are used, eg inductance, capacitance, electric resistance, magnetic resistance, are thought of as being fixed.

Any analysis of electromagnetic phenomena based on electric and magnetic circuit theory therefore gives approximate, imprecise results. In fact, such analyses will often produce meaningless results if they do not make use of electromagnetic field theory. The radiation and propagation of electromagnetic waves is a typical example of a problem which cannot be solved using ordinary circuit theory.

Offshore platforms are among the many industrial installations that depend on electromagnetic compatibility for reliable operation. **1**

Electromagnetic field theory

New developments in electronics have been at the center of many technological achievements in recent years, and the electronics sector is certain to carry on evolving dramatically in the future. Industrial equipment does, in fact, already today constitute high-tech electronics, and is destined to become faster and smaller with each new advance. The electromagnetic environment will also change dramatically; for example, modern radio and telecommunications equipment will be located closer and closer to the electronics, while the frequency range that is used will increase to several GHz. Also, maintenance crews will need to use modern telecommunications equipment in their jobs. This means that they will be increasingly confronted with electromagnetic field phenomena.

Obviously, a closer look needs to be taken at electromagnetic compatibility using electromagnetic field theory as a basis.

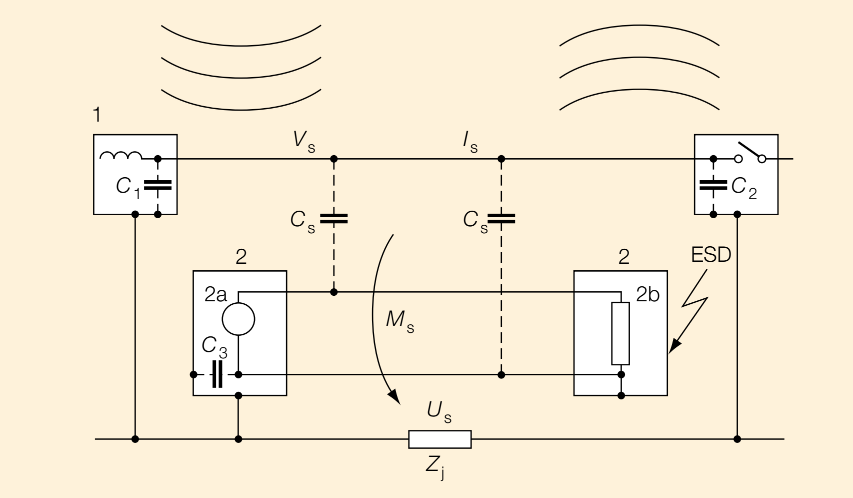
In order to correctly calculate circuit conditions it is necessary to first identify both the electric and the magnetic fields that exist in energized circuits. Knowledge of these electromagnetic fields is necessary not only to establish the circuit parameters but also to establish the characteristics of the electromagnetic phenomenon.

A complete analysis of the electromagnetic phenomenon can be performed on any item of equipment providing the current density, electric field strength and magnetic field strength, including their rates of change, are known. However, detailed studies are only possible when the characteristic field quantities are also known. Only by using Maxwell's equations can it be certain that solutions are reliable and complete.

Installations

In accordance with the 'Guide for the Application of the EMC Directive' (issued in 1998 by the Third Directorate of the European Commission and accepted by all member states), components with a so-called direct function and finished products for distribution or final use, as well as the systems in which they are used, have to carry the CE mark. However, the guide to application of the Directive only requires an installation to fulfil the essential EMC requirements; no requirements exist with regard to CE-marking of installations or approval by the competent body.

In everyday usage, the word 'installation' has come to mean a combination of different types of equipment, designed and assembled to perform a specific task; the end-user decides which equipment is used in its construction, and the combination as such is



Ways in which interference can be coupled into circuits **2**

1	*Interference source*	$C_1 – C_3$	*Stray capacitance*
2	*Victim*	C_s	*Coupling capacitance*
2a	*Signal source (transmitter)*	I_s	*Current*
2b	*Electronics*	M_s	*Mutual inductance*
		U_s	*Voltage*
		V_s	*Potential*
ESD	*Electrostatic discharge*	Z_j	*Earth-line impedance*

not intended for sale on the open market as a single functional unit. Such installations obviously have to be treated legally as systems without additional EMC requirements, since the EMC Directive will already have been applied to the individual items of equipment.

Fixed installations

Articles 1(1) and 2(1) of the EMC Directive apply to installations containing electrical and/or electronic components. A fixed installation, in the broadest sense, is defined as a combination of several types of equipment, systems, finished products and/or components (hereafter referred to as 'parts') assembled and/or erected by an assembler/installer at a given place and intended to operate together to perform a specific task in a defined environment, but not intended to be placed on the market as a single functional or commercial unit.

In a fixed installation thus defined there could also be parts which are not intended for use in the marketplace as single functional and commercial units (ie, *not* CE-marked). It makes no difference whether the parts come from one or more manufacturers, as the ultimate electromagnetic effect of the combined parts in the installation is simply not known by the vendor(s), who can only assume responsibility for each individual part officially placed on the market.

EMC problems involving equipment used in fixed installations are solved on a case-by-case basis, through cooperation between the manufacturers of the parts, the user and, when applicable, the installation contractor. The combined expertise of these parties ensures correct operation of the installation as a whole.

The people responsible for the design, engineering and construction (assembly and erection) become the 'manufacturer' in the context of the Directive, and assume responsibility for the installation's compliance with all applicable provisions contained in the Directive on being taken into service.

The EMC instructions provided by manufacturers of parts and also the method of installation have to correspond to good engineering practice as understood in the national, regional or local installation regulations. However, the design and manufacture of equipment already conforming to the Directive must not be influenced by this.

Such installations are not allowed to move freely within the EU market. No requirement for CE-marking exists; neither EC DOC (Declaration of Conformity) nor the involvement of a competent body is needed.

Coupling factors

It is extremely important to understand how interference arises in electronics and how its effect can be avoided or mitigated.

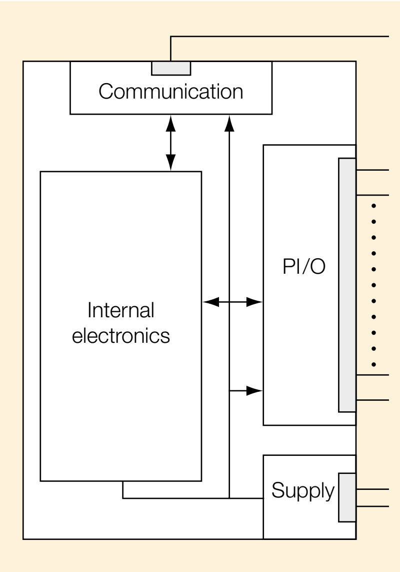
Interference is coupled into electronics in every technically conceivable way **2**, namely by:

- Induction
- Capacitance
- Conduction
- Radiation

Unwanted effects are avoided by reducing the degree of coupling into the equipment

Block diagram of an apparatus showing the interference barriers (grey areas) **3**

PI/O *Process input/output*



electronics. This applies particularly to high-frequency signals, where the interference signal and the useful signal are in the same frequency range (this is a new situation which has not been encountered in the past).

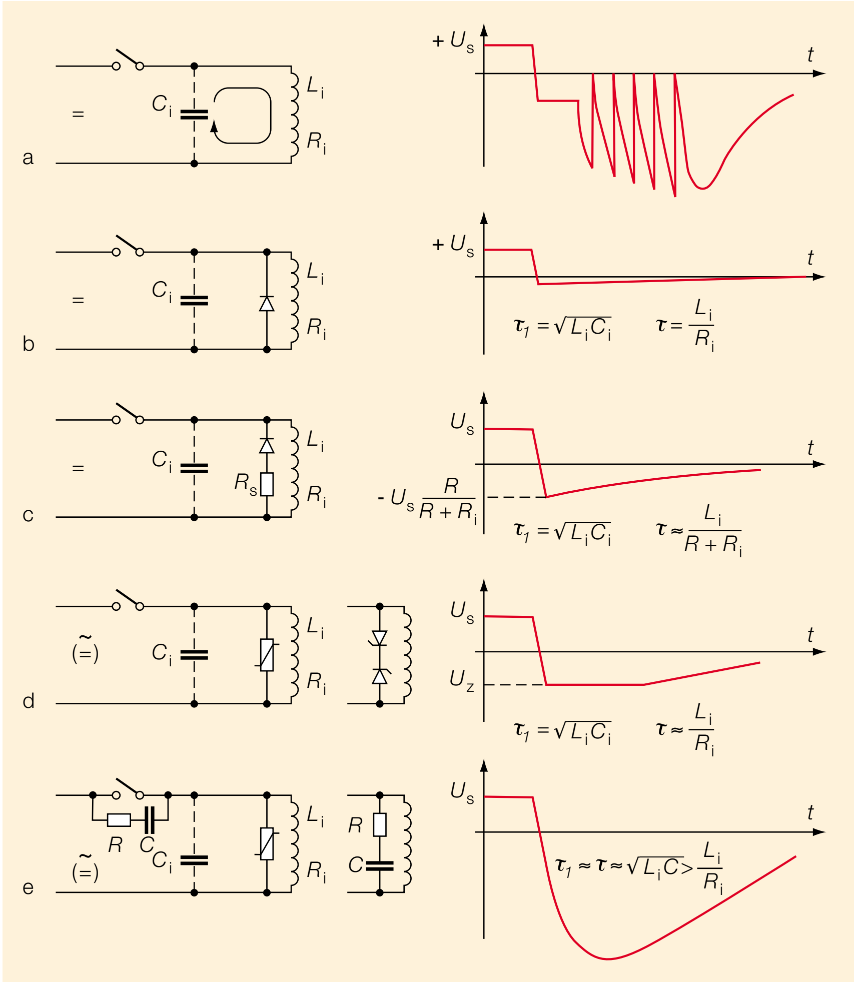
All interference can take the form of common-mode voltage (CMV) or normal-mode voltage (NMV).

Mitigating the effects of EMI

When working on any new product, the electronics designer alone is responsible for incorporating the interference immunity and emission aspects. The designer's awareness of this responsibility will be rewarded when the installed and commissioned system operates smoothly and without disturbance.

The interference immunity of an electronic product is mainly decided by the earthing, grounding and screening of the installation as well as the quality of the zero-volt plane and the barriers **3** in the electronics. Nevertheless, correctly designed and carefully chosen power supply units, analogue and digital circuit boards as well as communications, remain a prerequisite for a successful configuration.

The principle 'decrease the amplitude and frequency of the source as well as the coupling between the interfering circuit and the victim' should be adopted in order to successfully suppress electrical interference. This can be achieved by following certain rules:

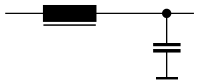
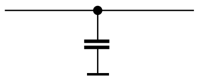
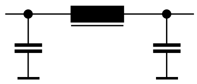
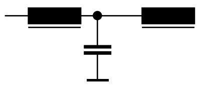


Methods of suppressing interference **4**

a *Not suppressed*
b *Suppressed with diode*
c *Suppressed with diode and resistor (DC circuit)*
d *Suppressed with varistor, TransZorb or 2 back-to-back zener diodes (AC circuit)*
e *Suppressed with capacitor and resistor (AC circuit)*

C *Snubber capacitance*
C_i *Stray capacitance*
L_i *Load inductance*
R *Snubber resistance*
R_i *Load resistance*
R_s *Suppressing resistance*
τ *Time constant of switching phenomenon*
τ_1 *Time constant of inductive load*
t *Time*
U_s *Source voltage*
U_z *Clamping voltage*

- Use an uninterrupted power supply.
- Separate the cables.
- Locate very sensitive cables as close as possible to the earth line or in the conduits.
- Use properly grounded (ie, with 360° connection) screened cables with acceptable transfer impedance.
- Use twisted-pair cables.
- Use overvoltage protection.
- Suppress interference sources **4**.
- Improve the environment (humidity) if electrostatic discharges cause a problem.
- Use a filter in power circuits **5**.
- Use a filter in signal circuits.
- Use 'chokes' **6**.
- Ensure correct connection of the cable screen.
- Protect against corrosion.
- Locate signal and return wire in same cable.
- Use conduits.
- Use an earth-line network.
- Use isolated circuits.
- Employ a total electromagnetic shielding concept.

Line impedance	Low-pass filter configuration	Load impedance
Low		High
High		High
High or not known		High or not known
Low		Low
Low or not known		Low or not known

Filter types for different applications **5**

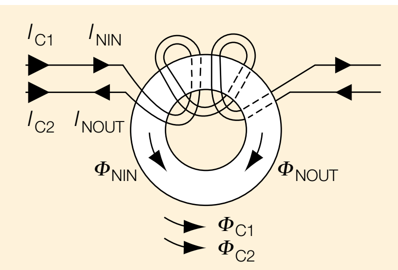
Electromagnetic shielding for total EMI protection

Only a total electromagnetic shielding concept, complete with filtering, will provide the desired overall protection against electromagnetic fields in every case. Assuming that the shield completely surrounds the object being protected, the electromagnetic wave will partly penetrate the shield and be partly reflected by it. If the material is sufficiently thick, the electromagnetic wave will be completely attenuated. (The shield has a dual function, ie it also protects the environment from electromagnetic fields originating inside the enclosure.)

Physically, the shield function is explained by eddy currents which are produced in the shielding material and which form an internal field that opposes the outer field. The required minimum shield thickness depends on the wavelength of the electromagnetic field. An electromagnetic wave is, in principle, completely attenuated in a conductive environment when the ratio of the amplitude before and after the shield is 0.00185.

Choke with high-frequency core for interference protection **6**

$I_{C1, C2}$ *Noise current (common mode)*
$I_{NIN, NOUT}$ *Load current (normal mode)*
$\Phi_{C1, C2}$ *Flux caused by noise*
$\Phi_{NIN, NOUT}$ *Flux caused by load current*



Magnetic shielding

To provide protection against undesirable magnetic fields, completely encapsulated enclosures made of ferromagnetic materials must be used. These enclosures, inside which the field is very much weaker than outside, are called magnetic shields **7**.

The use of ferromagnetic materials, which have a much higher permeability than space ($\mu \gg \mu_0$), results in concentration of the magnetic field density and passage of the field where the magnetic resistance is lowest. Thus, no field passes into the encapsulated space.

Protection against magnetic fields is often realized in steps (cascades) by means of 'enclosures within the enclosure'.

Nuclear electromagnetic pulses (NEMP)

While everyone hopes that civilization will never be confronted with NEMP, some buildings and installations of crucial importance to society must be protected against this phenomenon **8** to avoid the total collapse of society in the event of war or terrorist attack.

The same knowledge and principles can also be applied to provide protection against non-nuclear EMP pulses, eg pulses caused by certain atmospheric phenomena.

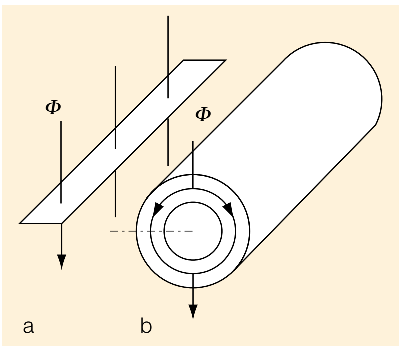
Strategy for dealing with NEMP effects

Before a project is started, an analysis is necessary to establish initial guideline estimates of the threats in the form of voltages, currents and fields expected at the interfaces. These are obtained by means of computations performed during the preparation of the technical specifications.

Large-area systems have to be divided analytically into subsystems which can be handled by test technology.

Magnetic flux, Φ, diverted by the magnetic shield **7**

a *Cross-sectional area*
b *Cable with magnetic shield*



The entire analysis, planning and testing procedure, including project management, is shown in simplified form in **9**. It is important to incorporate these measures in the project procedures at the earliest possible stage to avoid cost-intensive, and in some cases unsatisfactory, retrofitting later.

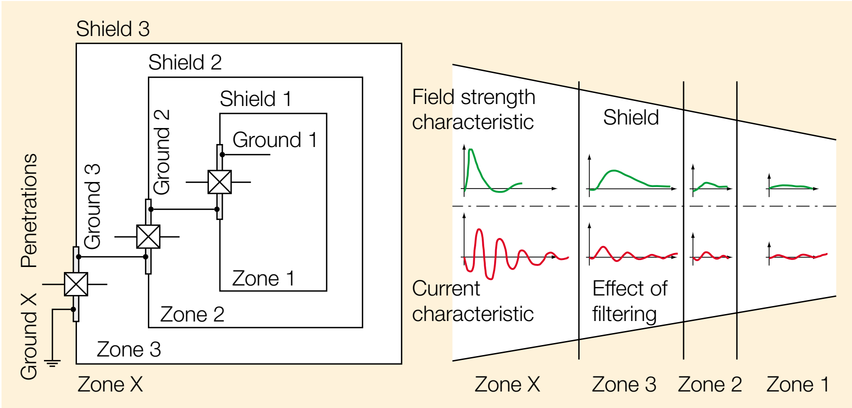
NEMP protection philosophy

American NEMP specialists divide the protection concept for ‘earth-based systems’ into three areas:

- *Topology* **10** (division into zones)
- *Penetrating conductors*
  Emphasis is justifiably placed on the great importance of shield-penetrating conductors. Here, decisive improvements can often be achieved by simple means, eg by bonding the cable screens at the apparatus input (360° connection). Spare leads are to be eliminated.
- *Aperture control*
  Only one aperture in the building **10** is to be used (and has to be as small as possible) at the buildingentrance. Apertures in a shield (for cooling pushbuttons, switches, potentiometer shafts, etc) are generally unavoidable. In fact, these apertures act as waveguides, and the shielding effectiveness in the case of certain frequencies can be altered by designing them correctly. To maintain good shielding effectiveness the cut-off frequency must be much greater than the operating frequency. Honeycombs are generally used for ventilation apertures. (Honeycombs are multiple waveguide elements arranged side by side, but the shielding effectiveness at frequencies well below the cut-off frequency is reduced by the number of elements.)

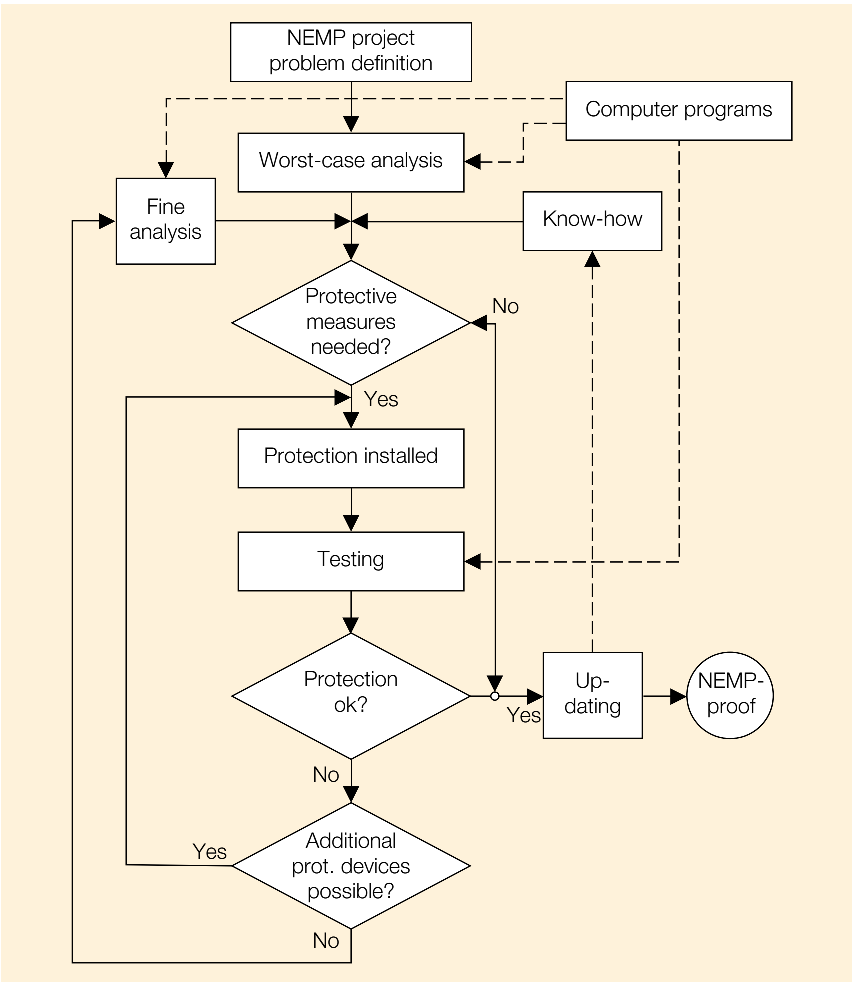
Theoretical analysis

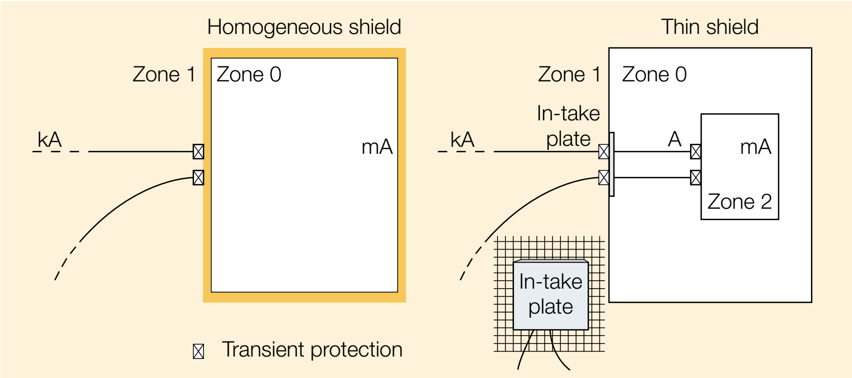
Since simulators normally cannot be used to study NEMP phenomena in large systems, theoretical analysis often has to be applied instead. Small software packages based on several simple subprograms and allowing fast, low-cost solutions are available for this. These are expected to replace the large and hence unwieldy computer codes still widely used for certain applications, and which require huge amounts of data as input as well as long data processing times.



NEMP protection zone concept **8**

Typical NEMP project procedures **9**





Topology zone concept. More zones can be connected as cascades. **10**

EMP-protected installations

When designing new NEMP-protected installations, eg facilities covered with layers of earth, it might be advantageous to include the steel reinforcement skeleton in the zonal concept **11**. In the low-frequency range (10 kHz) this could result in a gain of approximately 20 dB in magnetic shielding effectiveness. A prerequisite, however, is correct welding of the reinforcement bar crossings.

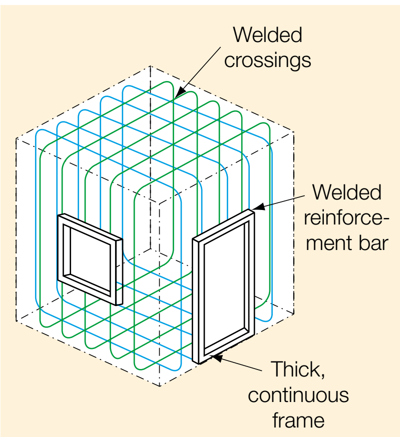
Special filters for NEMP and EMP applications

The electromagnetic radiation caused by nuclear explosions depends on the height at which the explosion takes place. An explosion at a very high altitude generates a very powerful field of about 50 kV/m. The electromagnetic pulse has a very short rise time, typically less than 10 ns. A special, technologically advanced filter can be included in the NEMP protection. NEMP filters are a part of the general protective configuration, usually with specific features such as:

- A primary protective arrangement designed to shunt the majority of the undesired energy to ground.
- A delay arrangement in which the incoming pulse is slowed prior to entering the filter. The filter is very often fitted some distance away from the primary protection, eg on the other side of the wall.
- A secondary protective arrangement, normally provided in the form of a zinc-oxide varistor fitted across the filter terminals (attachment contacts) which reduces the electromagnetic pulse.
- A filter in each phase and in the neutral. Filtering by means of a common core is not recommended as a powerful pulse can cause the cores to lose their low-frequency features.
- Multiple filters. More filters can be connected in parallel to increase the nominal value of the current without increasing the losses. The current can be distributed in the particular branches by means of busbars. Special attention must be paid to shielding as well as to electrical safety.

The NEMP filter should be used in shielded rooms as well as in all facilities in the ground, water and air designed to provide NEMP protection.

Cost-effective shielding concept **11**



Conclusions

Sound theoretical knowledge of all the problems involved is essential in order to fulfil the legal and specific EMC requirements of customers. The ABB Group is able to meet not only the legal stipulations, which should be considered as the minimum level of EMC required, but also the most demanding requirements in this extremely challenging and controversial field. Furthermore, the ABB Group can transfer this know-how through consultation and training to anywhere in the world.

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Author

Dr. Sten Benda
ABB EMC Certification AB
SE-721 67 Västerås
Sweden
Telefax: +46 21 14 31 43
E-mail:
sten.benda@seisy.mail.abb.com

A new analyzer for more accurate cooking liquor measurements

After decades of conservatism, the wood-pulping industry has broken the mould and started to install more sophisticated processes and process control systems. The driving forces have been mainly environmental issues, but there has also been increased demand for higher pulp quality. Processes introduced recently to the batch digesting field, for example, have improved the overall energy economics and also brought the desired progress in the environmental and quality areas. However, they have also led to the re-use of spent cooking liquors of varying concentration, creating a need for more accurate measurement. The CLA 2000™ is a novel cooking liquor analyzer that meets this need while providing data that assist in the process management. Improved pulp quality and yield, reduced chemical consumption and lower maintenance costs are among the benefits.

In today's high-capacity digester houses, a production 'batch' represents a high material tonnage, so that poor quality in a batch can significantly reduce the final pulp quality. Unfortunately, it can be very expensive, and sometimes impossible, to correct a loss of quality in the fiber line process due to the kappa numbers being too high or too low during cooking. Because of this it is widely recognized that 'pulp quality is decided during cooking – later, it can only be degraded'.

In kraft (sulfate) cooking, alkali measurements have been used for some time to determine the chemical consumption during the different cooking phases. These measurements are widely accepted as the standard monitoring information as they provide a solid basis for the cooking management. However, the method alone no longer meets the needs of the industry. What is also needed is information that tells the cook how well the different wood constituents have dissolved.

The compound that has to be removed from the fibres is lignin, a complex organic polymer deposited in the cell-walls of the plant. One problem is that the dissolving process cannot be allowed to continue for too long or it will cause a drop in the pulp yield and a loss of quality. To monitor the process, the dissolved lignin and the total dissolved solids (TDS) can be measured separately and the difference between them used as an indication of the loss of yield.

Raimo Sutinen
ABB Industry Oy

Various research programmes which are under way have started to shift their focus to ways of improving the final quality parameters, such as pulp strength. Increasing interest is also being shown in the cooking yield, which is the dominating factor in the overall economics of a pulp mill. As a result of these trends, new methods of measurement which can also determine the dissolved wood material concentrations are required.

Background

Improving quality and productivity are long-standing goals of the process industry. Over the years new variables have been introduced which need to be accurately monitored and controlled, making new demands on measurement technology. The CLA 2000™ is a novel analyzer, based on a continuous flow sampling technique, which provides the necessary multi-measurement platform. Developed to handle liquid samples, its first application is in pulp mills, where it is used to measure alkali content and the total dissolved solids and dissolved lignin concentrations. The information provided by the system is also used in process control.

The purpose of cooking in a pulp mill is to remove lignin, the compound holding the cellulose fibers together. Lignin is removed by cooking with chemicals ($NaOH + Na_2S$) at high temperatures (140–170 °C). The degree of lignin removal is expressed as a so-called kappa number. The kappa number is analyzed in the laboratory using standard means or determined optically by measuring the ultraviolet light absorption with on-line analyzers after cooking.

Kappa-number analysis is based on the reaction of permanganate with lignin. The kappa number expresses the number of milliliters of 0.1 – normal potassium permanganate consumed by one gram of dry pulp in 10 minutes under controlled conditions.

CLA 2000 cooking liquor analyzer. Besides allowing accurate measurement of the liquor concentrations, the CLA 2000 also provides data that assist in the process management. **1**

CLA 2000™ – a cooking liquor analyzer based on advanced sampling

Analyzers for the process industry are typically built to be used in a harsh environment. This applies especially to cooking processes, in which the process liquors have a temperature of 150 °C or higher at pressures of up to 20 bar, and the liquor itself is highly corrosive and capable of causing extremely severe scaling. In view of this, ABB has invested a lot of effort in the design of a system which can guarantee reliable, continuous operation, coupled with an acceptable level of maintenance. The system makes use of high-quality materials, and the number of moving, and therefore wearing parts, has been kept to a minimum; cleaning of the system is automatic and reliable.

Called the CLA 2000 cooking liquor analyzer **1**, it is based on a new, advanced sampling technique **2**. The analyzer draws a continuous sample flow from the process, allowing continuous measurement when one CLA 2000 measuring unit is dedicated to a single sample point. The performance of the CLA 2000 represents a dramatic improvement over conventional sampling systems, which take just one sample, eg at 5-minute intervals. Another benefit is that no control valves are used; these tend to wear quickly in such a harsh environment. Basically, the system can be used to sample every kind of process liquid providing it is under at least some pressure.

Connection to the process is simple **3**; a nipple, a manual shut-off valve and a unique adaptive spiral filter which prevents harmful solids from entering the sensor units are all that is required. The spiral filter utilizes the principle of variable gap filtering and is designed to standards that guarantee high reliability.

The sampling system contains a heat-exchanger which cools the sample and also serves as warm wash-water reservoir. Both the sample and wash water are held at the sample temperature, which is higher than the ambient temperature, to eliminate condensation and contamination problems.

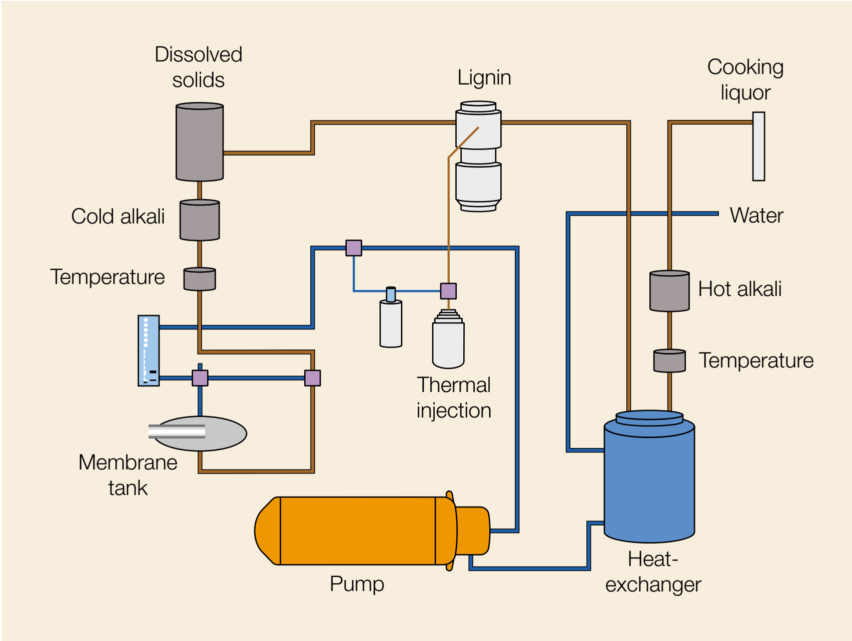
Following the heat-exchanger is an array of robust sensors. Measurements are carried out without any dilution of the normal process concentration. The sensor array includes conductivity sensors for the alkali measurement, a refractive index sensor for measuring the total dissolved solids and a UV-absorption sensor for the dissolved lignin measurement. Further sensors can be added to this platform if required.

In the next step the sample flows into a membrane tank, which separates water from the process sample to inhibit corrosion. The membrane tank also controls the sample cycle. After the tank has been filled by the continuous sample flow the system starts a high-pressure pump, which quickly returns the sample to the process together with clean water, thereby cleaning the sample lines. Typical running times are 9 minutes for the sample flow and 1 minute for the back-flush (the 1 minute is negligible in processes such as cooking). Some adjustment of the cycle is possible, being dependent on the number of sample points included in the measuring unit.

The sample flow rate is controlled by a constant flow regulator installed in the water line after the membrane tank. Regulation of the sample flow thus takes place with pure water and is independent of variations in the process pressure.

Washing is carried out with clean warm water at high pressure. All the flows are controlled by mechanical and non-return pressure reduction valves; no control valves which are subject to wear are used. The system also offers the option of automatic injection of a cleaning agent. This is recommended where conditions are more severe, eg in the transfer circuit of continuous digesters. The main purpose of the automatic injection is to keep the UV-measurement cell clean. Cleaning agent consumption is minimal.

Software for sampling, measurement, back-flushing and communication is included in the CLA 2000 electronics unit. A field-proven user interface is also provided for maintenance purposes.



Operation of the CLA 2000™ cooking liquor analyzer is based on a continuous flow sampling technique **2**

Special sensor technology is used for measurements

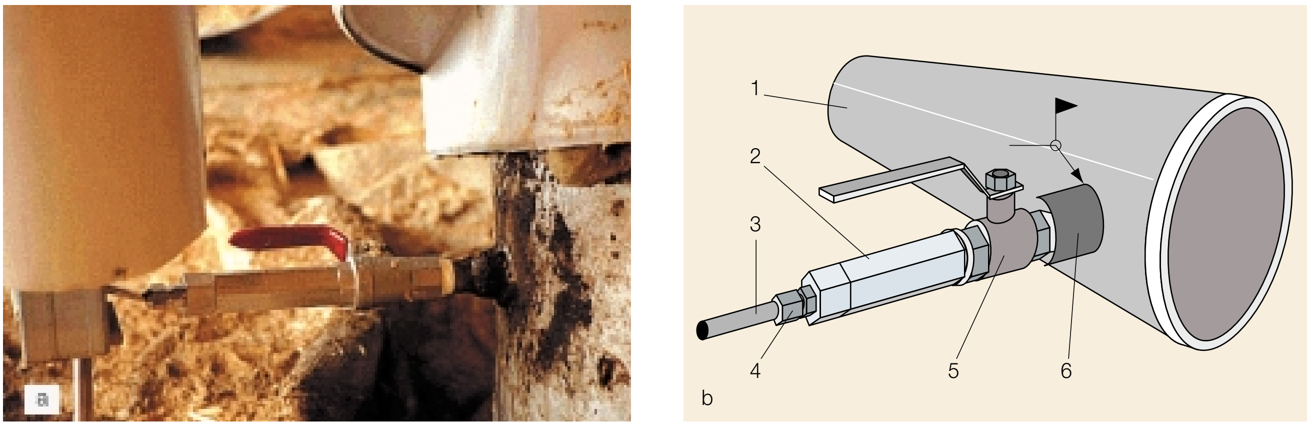
The key element in any measuring system of this kind is the sensor array. Special attention was therefore paid to the sensor technology used in the CLA 2000. In kraft cooking, for example, the CLA 2000 measures alkali, dissolved lignin and the TDS concentrations in samples of different cooking liquors.

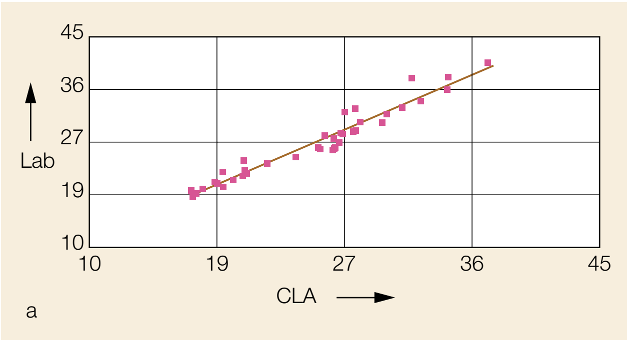
Alkali

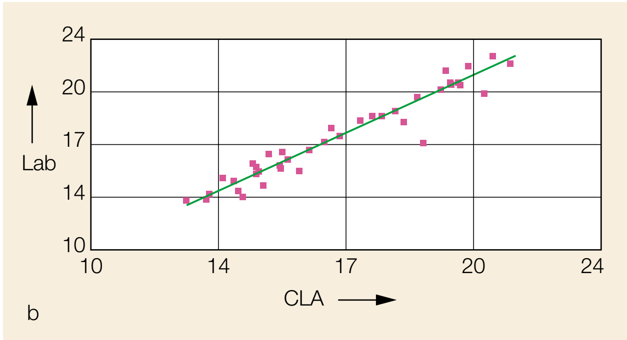
The alkali measurement is based on a unique dual-sensor principle. Temperature compensation is a crucial factor as the temperature has a strong influence on the conductivity. The conventional way to compensate for temperature is to perform experiments based on certain process conditions. This is usually done in the mill itself. The drawback of this method is that it does not take into account other variations in the process, for example differences in concentration. Tests in the ABB

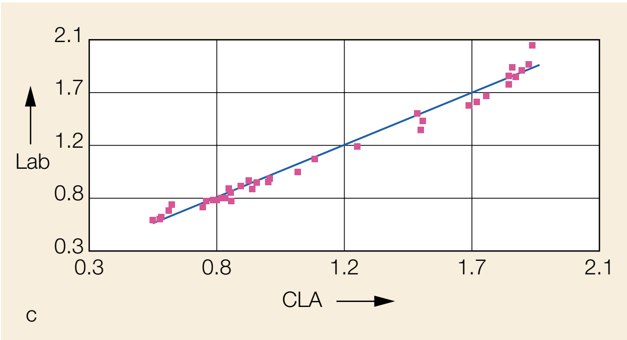
Close-up (a) and schematic (b) of the simple process connection **3**

1 *Process line*
2 *Spiral filter*
3 *Sample line*
4 *Connector*
5 *Shut-off valve*
6 *Nipple*









4

Results of a three-week test run in sulphate batch digester house cooking softwood: measurements with CLA 2000 versus laboratory analysis

a *Alkali (R^2 = 0.975)*
b *Total dissolved solids (R^2 = 0.980)*
c *Dissolved lignin (R^2 = 0.992)*

(R^2 = Correlation coefficient)

laboratory have shown that these variations can cause an error in the conductivity reading of up to 20 % under normal process conditions. The dual-sensor used for the alkali measurement in the CLA 2000 measures the same liquor at two temperatures, the first time at the process temperature of, eg 150 °C, and afterwards downstream of the heat-exchanger, where the temperature is controlled to 40 °C. The effect of temperature on the conductivity is therefore monitored continuously, and accurate temperature compensation is ensured. Another benefit is that the time-consuming field calibrations are minimized.

Dissolved lignin

The determination of the dissolved lignin is based on measurement of the UV-light absorption. Conventional UV-measurement requires high dilution, typically 1/1000 or even 1/2000, due to lignin's strong absorbency of ultraviolet light. The CLA 2000 measures the dissolved lignin in its actual process concentration. Instead of high dilution, a short optical path is used – a completely new approach for process analyzers. This advanced method is more accurate and the measurements are more representative. Also, since there are no complicated dilution systems, the system design is simpler. Maintenance is also reduced.

Total dissolved solids

The determination of the TDS combines the refractive index principle with digital measurement, thus eliminating the problems associated with conventional systems, such as drift, noise and frequent calibration. A polished sapphire prism and special flow arrangements ensure that there is no contamination.

Measurement accuracy

Tests have been carried out to study the accuracy of the CLA 2000. The first of these included comparison of the CLA 2000 readings with actual measured physical parameters (ie, conductivity, refractive index and UV-light absorption). The tests were performed in a laboratory, and standard solutions as well as actual kraft liquors were used, in each case with different concentrations, temperatures and pressures. To study the accuracy of the system under real process conditions, tests were also carried out in several mills. These involved both batch and continuous digesters and covered hardwood and softwood liquors. Comparisons were made with the results from standard laboratory tests performed in the mills. In the case of the dissolved lignin measurement, a high-precision laboratory spectrophotometer had to be used in most cases as mills do not usually have the equipment needed for a direct analysis of the lignin content. The results of a three-week test run carried out in a sulphate batch digester house cooking softwood is shown in **4**.

The results of these studies may be considered as excellent, bearing in mind the accuracy of the laboratory methods and the fact that the sample can change somewhat prior to the analysis. The alkali tests are especially susceptible, and the tests have to be performed as soon as possible after the samples have been taken. *Table 1* summarizes the CLA 2000 measurement correlation, referred to the laboratory analyses, for different mill tests.

Kappa-number prediction

Ongoing development of the continuous cooking process has brought about new methods, such as Modified and Extended Modified Continuous Cooking (MCC/EMCC) and IsoThermal Cooking (ITC), as well as so-called Low Solids Cooking from another process equipment vendor. These new methods have introduced additional circuits with different alkali and solids concentrations.

As already mentioned, the kappa number has traditionally been used as the main quality indicator in kraft cooking. As the kappa number is measured in the blow line after the digesters the feedback necessary for the cooking management is received very late in the process, and can be delayed by as much as several hours. Also, in spite of automatic kappa-number analyzers being used widely, especially in continuous cooking processes, the samples used for cooking feedback are taken more or less infrequently. If the analyses have to be carried out in the laboratory feedback will be even less frequent; for example, 2-hour intervals are quite typical for the industry.

Since the CLA 2000 measurements show the consumption of the cooking chemicals and the extent to which the wood material has dissolved, it is a logical step to use this information to predict the cooking result. The main benefit of this is that the information becomes available during the actual cooking and not just in the blow line several hours later, when the conditions under which the pulp batch was produced no longer exist.

The reliability of a mathematical model depends on the nature and behaviour of the process actually in progress being thoroughly understood. Besides being laborious, costly and time-consuming, such a methodology assumes that all the required process information is available. Often, however, the process is highly complicated and consequently not completely understood. A different approach is therefore called for – preferably one which provides the required information via the available process measurements. The CLA 2000 analyzer records precisely the kind of information that is needed while the cooking is in progress and makes it available for modelling.

Modelling was carried out using data from different types of batch and continuous digesters, and applying the least squares fit and artificial neural network methods. Neural networks are appropriate for mills as an on-line kappa-number device can also be used to provide the large amounts of data that are needed for the network training. However, the most important aspect of network training is the quality of the data; data containing too much noise or insufficient information will result in poor results that do not allow reliable generalizations to be made.

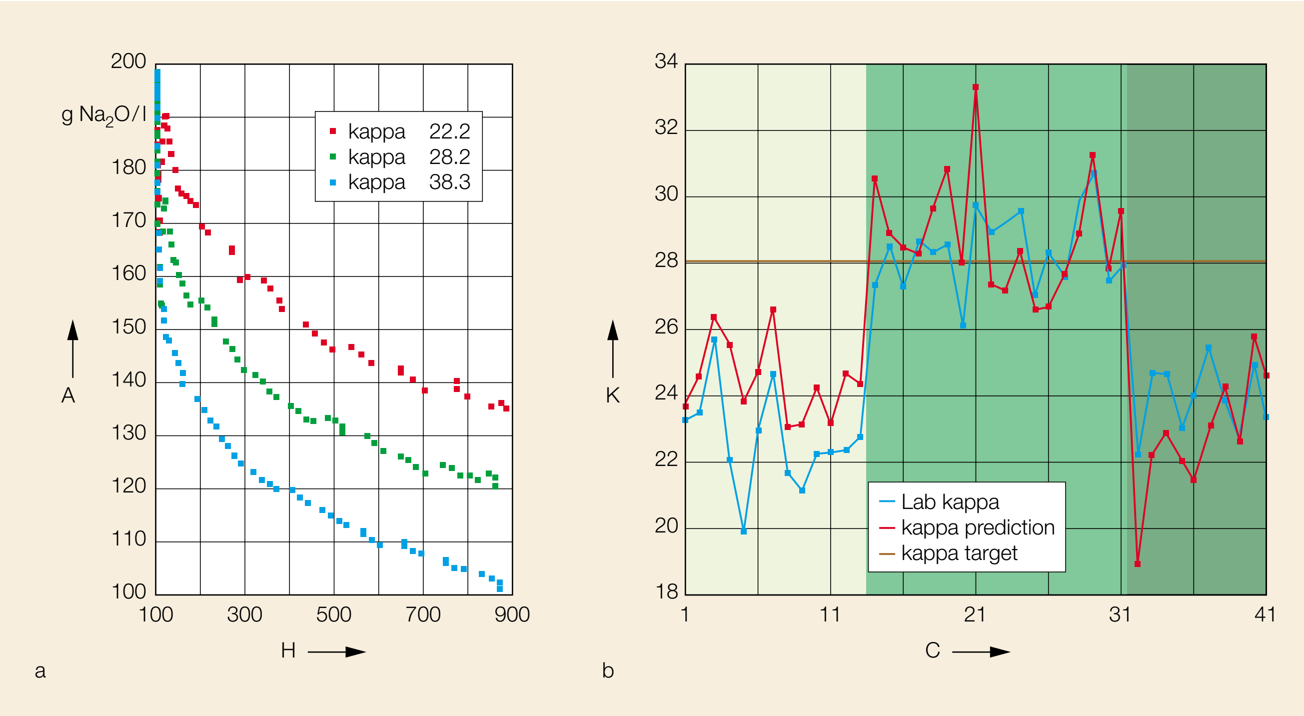
Kappa-number prediction equations were generated during batch digester house tests based on CLA 2000 measurements made at one or two points during cooking. It was assumed that each measurement described the state of the process at that instant and how cooking had progressed. Using the generated equations, the target H-factor (ie, the time integral of the cooking temperature) was determined that gives the desired kappa number for all the production batches. This reduces the kappa-number deviation, improves the pulp quality and reduces the cost of chemicals in the bleaching plant.

Another approach to monitoring the progress of cooking is to use reference curves obtained by plotting CLA 2000 readings against the H-factor for different kappa-number bands 5a. This method is especially appropriate for digester houses with a large number of digesters and where the kappa-number samples are

Table 1
CLA 2000™ measurement correlation

Mill	Type	Wood	Alkali	R^2 TDS	Dissolved lignin
A	Batch	SW	0.975	0.980	0.992
B	Continuous	SW	0.994	0.996	NA
B	Continuous	HW	0.997	0.993	NA
C	Batch	SW	0.978	0.968	NA
D	SuperBatch	SW	0.974	0.958	NA
D	SuperBatch	HW	0.980	0.981	NA
E	SuperBatch	SW	0.993	0.958	NA
F	Continuous	HW	0.983	0.996	0.991

R^2 *Correlation coefficient*
SW *Softwood (pine)*
HW *Hardwood (birch)*
NA *Not available*



Alkali reference curves (a) and graph of predicted versus laboratory kappa numbers (b) based on CLA 2000 data and reference curves for three digesters **5**

A *Alkali*
H *H-factor*
K *Kappa number*
C *Cook number*

Light green *Digester 1*
Medium green *Digester 5*
Dark green *Digester 11*

taken manually. As can be seen, CLA 2000 measurements give quite a good indication of how well the cooking is progressing during the early stages of digestion. **5b** compares laboratory kappa numbers with predicted kappa numbers, based on CLA 2000 data and reference curves for three digesters. It is worth noting in this context that digesters perform differently even when the conditions are the same.

In a continuous digester house the CLA 2000 can measure variables in several digester circuits. Typical measurement points are the transfer and trim (cooking) circuits and the extraction flows, but measurements have also been taken in the counter-current and wash circuits. It is easier to collect the kappa-number samples in a continuous digester house than in batch digester houses. Often, an automatic kappa-number analyzer is also installed.

The results obtained with the kappa-number prediction method have been very encouraging. **6** shows results from an EMCC-type continuous digester house. The initial data, up to Feb 6, are used as training data, while the rest are independently predicted. The prediction method used was based on a so-called back propagation neural network. Blow-line kappa numbers were collected and evaluated by an automatic kappa-number analyzer.

When the end results are obtained during the actual cooking process, rather than several hours later, control strategies can be developed to correct any unwanted deviations in the cooking conditions before it is too late. The results are less off-spec pulp, improved overall pulp quality and reduced bleaching chemical consumption.

Future trends

As already mentioned, the kappa number has traditionally been the main variable used to indicate the pulp quality in sulphate pulping. However, much of the research today is focusing on 'real' pulp quality properties in cooking, such as the tear and tensile strength. Also, the cooking yield is very important as it directly affects the economics of the process.

The purpose of cooking is to dissolve the lignin – the compound holding the cellulose fibers together. This has to be done without dissolving the fibrous material for too long, ie without removing too much of the hemicellulose and cellulose. Even with today's technology this kind of yield loss cannot be totally avoided, but it can be reduced by optimized control of the cooking.

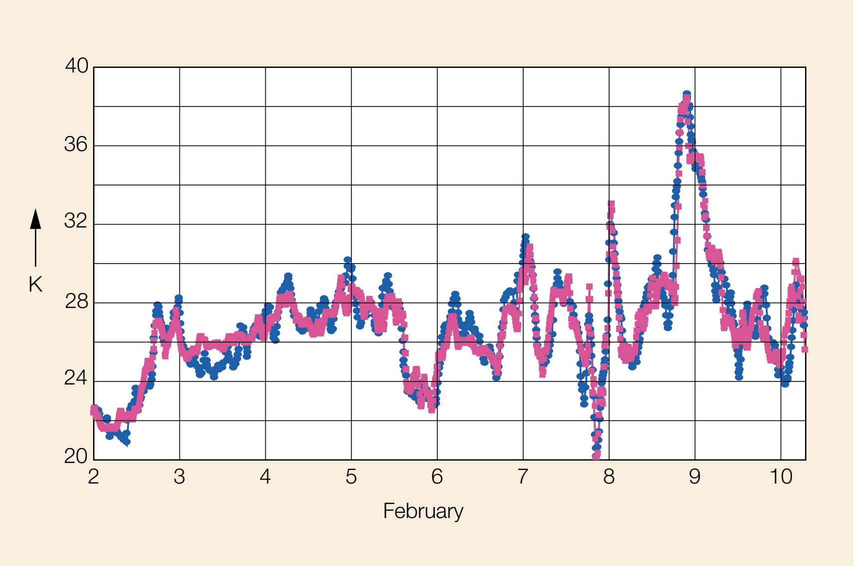
The effect of the different alkali profiles on cooking has been studied in several recent research projects [1]. They have shown that the alkali profile should be smoother than the conventionally used profiles, preferably by using lower alkali concentrations at the beginning of the cooking and adding alkali in the later stages. This will reduce the required H-factor, so that cooking temperatures can be kept relatively low, which further improves the pulp homogeneity and properties such as strength and bleachability.

7 shows an example from a batch digester house where the lignin-dissolving process has slowed while the total solids have continued to dissolve. This indicates that dissolving of hemicellulose has accelerated, resulting in yield losses. In other words, cooking has continued for too long beyond the optimum point. Measurement of the dissolved materials and appropriate control strategies allow this situation to be improved. The peak in the alkali curve was caused by the addition of white liquor after about 55 minutes.

Recent studies have also proved that the quantities of dissolved organic compounds in the cooking process affect the pulp characteristics. The amount should therefore not be high at any time during the cooking. Reducing the amount of dissolved organic material leads to a better tear-tensile curve, lowers the consumption of cooking chemicals and improves the pulp bleachability.

It has also been shown that dissolved wood solids consume alkali in non-productive, secondary reactions, and weaken the selectivity of pulping. Keeping the solids profile in the digester optimized will allow a reduction in the white liquor consumption, or alternatively a lower cooking temperature with a constant white liquor dosage. This improves the cooking selectivity and results in improved pulp viscosity. Improvements in brown stock washing, such as reduced chemical oxygen demand (COD) have also been reported [2].

Since it measures both the dissolved lignin and the total dissolved material, the CLA 2000 is an excellent tool for cooking management.

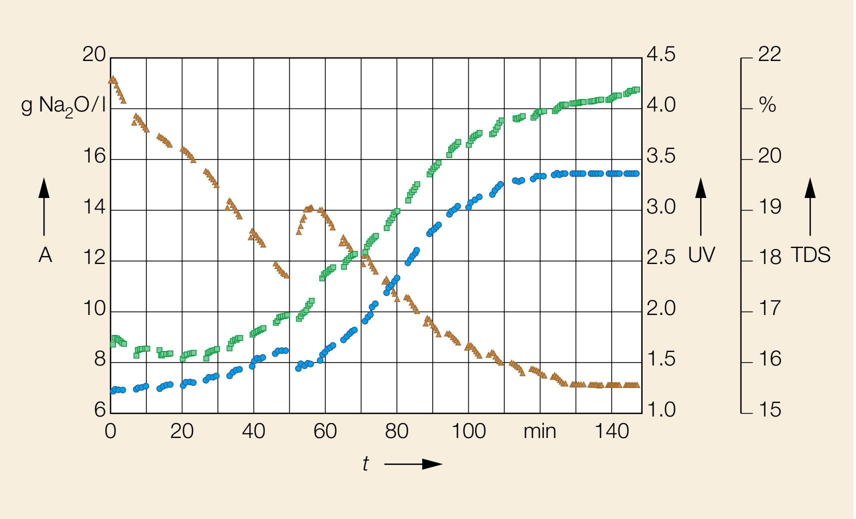


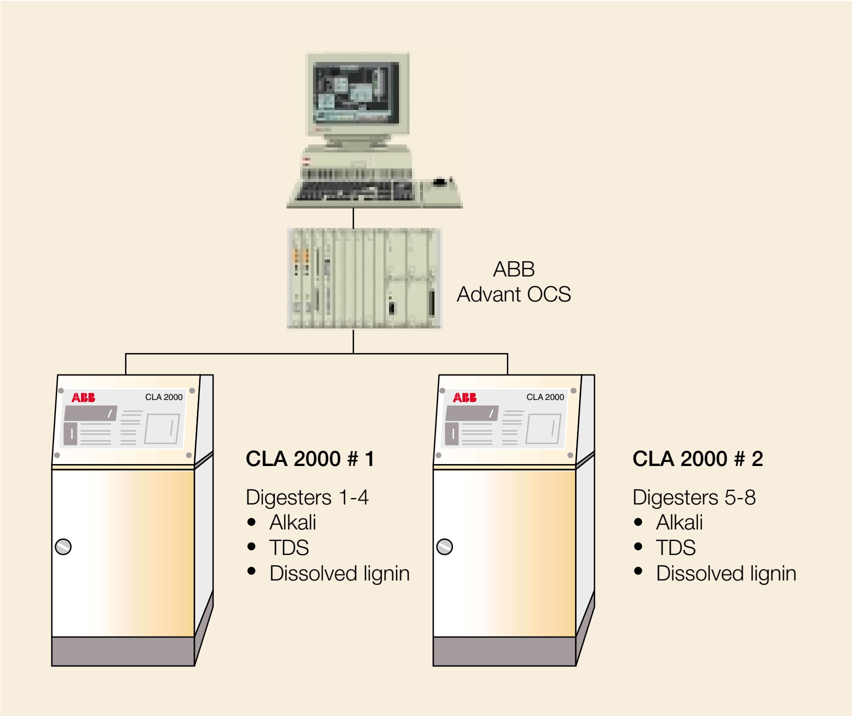
Predicted versus laboratory kappa numbers (K) for a continuous digester house 6

Blue *Kappa number*
Red *Kappa predictor*

Cooking concentrations measured with the CLA 2000 analyzer in a batch digester house 7

A *Alkali (brown curve)*
UV *UV absorbance (blue curve)*
TDS *Total dissolved solids (green curve)*
t *Time*





Process control configuration with CLA 2000 at a mill operated by SCA Packaging Obbola AB in Sweden. Process data include: conventional batch digestion, kappa level 70–100, AutoCook/B, and CLA 2000 kappa control. **8**

Process control

CLA 2000 measurement information can be used for direct process control in a number of ways. A straightforward solution is to use it for alkali dosage and alkali profile control. (Field solutions will obviously vary in accordance with the digester house configuration.) In a next step it can be used to control the solids profiles in those digester houses where it is applicable. And finally it can be used for on-line kappa-number control with process management systems, eg Auto-Cook.

Possible applications include basic alkali dosage control, alkali trim control, batch and continuous digester cooking profile control, and kappa-number control. A projected feature is washing efficiency management, while the final target is yield and strength property management.

Experience in mills

CLA 2000 has been installed in several mills, both of the batch and continuous digester type. The system has performed well and reached all of the set targets. Measurement accuracy and repeatability have proved to be at a very high level, and the maintenance requirements are clearly below the previous level for such types of analyzer. The typical maintenance required is a short check of the system once every week or two. Some preventive maintenance is required every six months.

The system has also been in use for more than two years at a mill operated by SCA Packaging Obbola AB **8** in Sweden. Experience with the system in this mill has been very encouraging; maintenance requirements are not only generally modest but are also dramatically lower than with the previous analyzer.

In addition, the mill has experienced a 30–50 % reduction in kappa number standard deviation by using CLA 2000 measurements in its control strategy.

Summary

CLA 2000 provides a multi-measurement platform suitable for analyzing all process liquids. In its first application – for cooking liquors in pulp production – special attention has been paid to high long-term reliability, measurement accuracy and low maintenance requirements.

The system can be used as a stand-alone analyzer or integrated into on-line control.

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Author

Raimo Sutinen
ABB Industry Oy
Tyrnäväntie 14
FI-90400 Oulu
Finland
Telefax: +358 10 22 52 140
E-mail:
raimo.sutinen@fi.abb.com

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CH-8050 Zurich, Switzerland