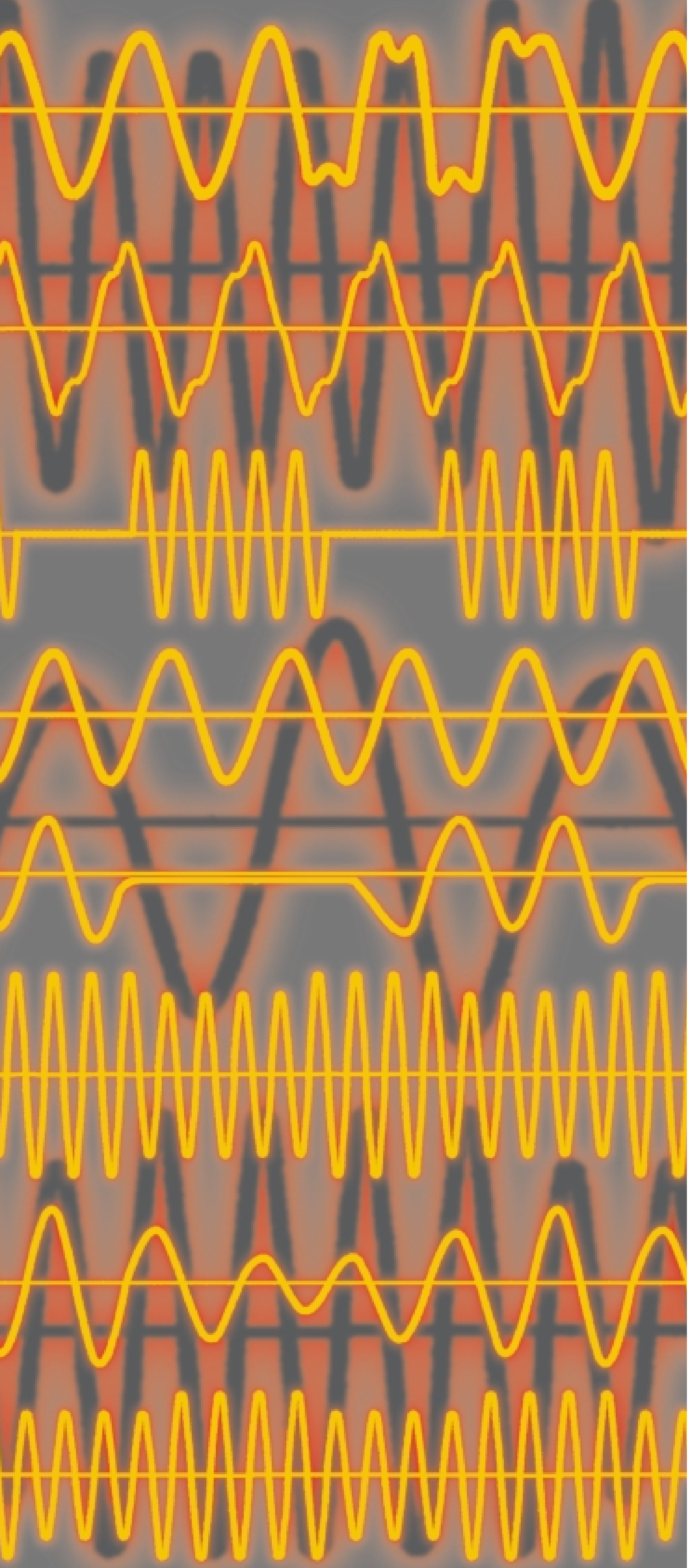

# ABB Review

3/98

Innovative system solutions for power quality enhancement

New simulation tool for modelling and analyzing power quality problems

Intelligent high-voltage substation automation

Steam turbines retrofitted in record time

How reference power plants speed up construction and lower costs

Hybrid trucks in commercial service

ABB

# ABB REVIEW

ABB is an international company firmly committed to electrical engineering. It has industrial bases on all continents and is represented in over 140 countries. Its major businesses are power plants, power transmission, power distribution and industrial equipment; other important business activities are in the robotics and environmental sectors.

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Rütistrasse 6
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Tel. +41 56 205 48 36
Telefax +41 56 221 22 74
E-mail internet address:
abbreview.chmar@chcms.mail.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

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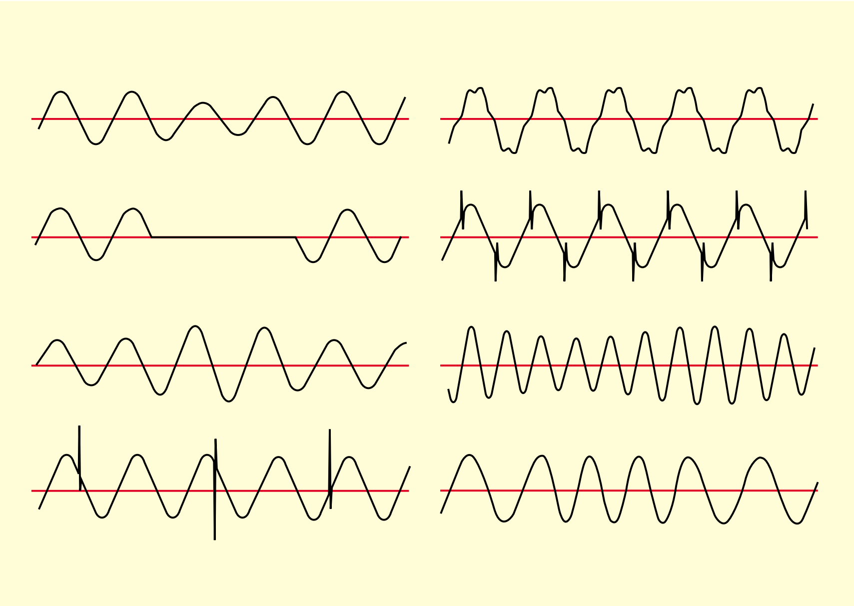
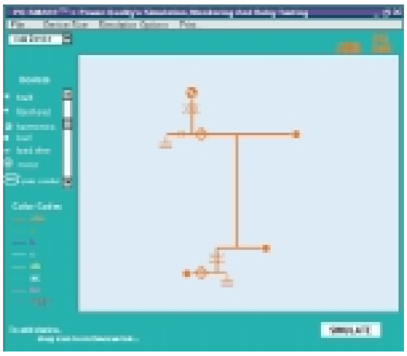
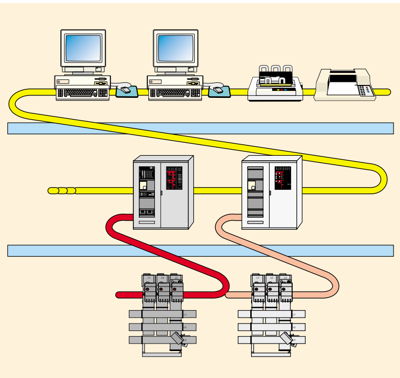
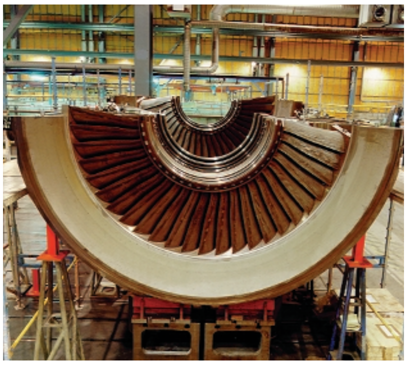




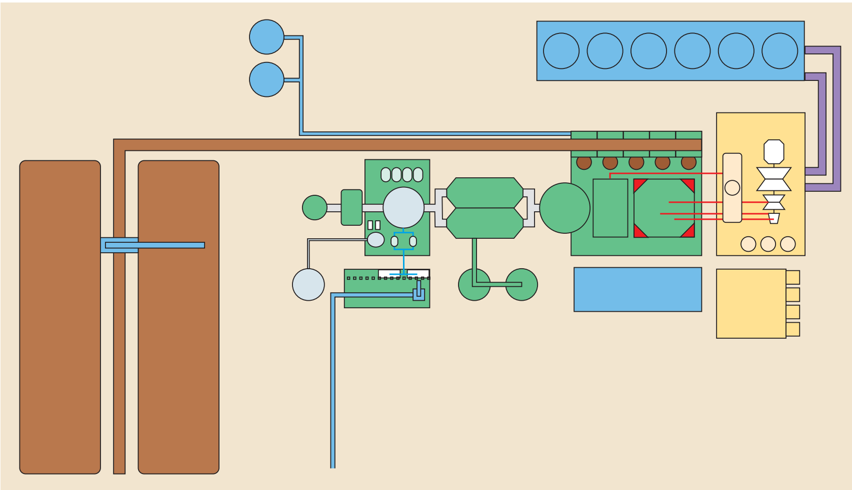






**Low-pressure steam turbines** in a nuclear power plant in Finland were recently retrofitted after studies had shown them to have the greatest potential for increasing steam cycle efficiency through the use of advanced technology. As a result of the retrofit the plant output was increased by almost 5 percent, or 36 MW.

**Page 27**



**Modular reference power plants** are designed with features that, in addition to lowering costs, considerably shorten the time needed to plan and build steam power plants. The concept was developed for the emerging markets as well as the highly industrialized economies. Plants with unit ratings of 175, 300, 600 and 900 MW are available.

**Page 33**


**Hybrid drive lines** – a combination of electric motor and internal combustion engine – help to reduce the environmental impact of road traffic by lowering vehicle emissions. A three-year commercial trial with two Volvo trucks fitted with such a drive has begun in Gothenburg, Sweden. The trucks can also run entirely without emissions in especially sensitive environments.

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# THIS ISSUE

# Innovative system solutions for power quality enhancement

**The privatization of utilities and the deregulation of the electrical energy market have introduced a new level of competition to the energy supply business. At the same time, the increasing use of electronics in everyday appliances and apparatus, plus a proliferation of highly sensitive end-user devices, are starting to draw the attention of consumers and energy suppliers alike to the issue of power quality. Solid-state transfer switches as an alternative to in-house uninterruptible power supplies, distribution static synchronous compensators for reducing flicker produced by arc furnaces, and dynamic voltage restorers that avoid production losses caused by voltage sags, are among the innovative solutions addressing the question of power quality.**

Power quality problems are caused by a wide range of phenomena. About two thirds of these are natural phenomena, such as lightning. Other sources of power quality disturbance, for example the operation of power system equipment (eg, capacitor switching) may be found in industry, or within the power system itself, where faults may cause a voltage sag at the consumer end.

IEC (1000-2-2/4) and CENELEC (EN50160) standards define power quality as the physical characteristics of the electrical supply provided under normal operating conditions that do not disrupt or disturb the customer's processes. UNIPEDE also includes the supply availability as part of this definition. Power consumers with sensitive or critical loads need a constant network supply voltage with a sinusoidal waveform at nominal frequency and magnitude. A power quality problem therefore exists if any voltage, current or frequency deviation results in maloperation or failure of a customer's equipment.

The growing concern about power quality stems from:

- Consumers becoming increasingly aware of the power quality issues and being better informed about the consequences of interruptions, sags, switching transients, etc. Motivated by deregulation, they are challenging the energy suppliers to improve the quality of power delivered.
- The proliferation of load equipment with microprocessor-based controls and power electronic devices which are sensitive to many types of power quality disturbances.
- Emphasis on increasing overall process productivity, which has led to the installation of high-efficiency equipment, such as adjustable speed drives and power factor correction equipment. This in turn has resulted in an increase in harmonics injected into the power system, causing concern about their impact on the system.

**Arun Arora**
**Kevin Chan**
**Thomas Jauch**
**Alexander Kara**
**Ernst Wirth**
ABB High Voltage Technologies Ltd

A low-quality power supply may cause disruption of a customer's process, leading to a loss of revenues. It is therefore in the interest of customers to ensure that the process downtime caused by poor power quality is minimized. Conversely, a customer's process may affect the supply quality, and it is in the interest of the utility that this effect be minimized. To improve power quality, a partnership that brings together the customer, utility and equipment manufacturer is clearly needed.

### Problem areas in power quality

Power quality problems are evident in many commercial, industrial, residential and utility networks. As mentioned above, natural phenomena, such as lightning, are the most frequent cause of power quality problems. Switching phenomena resulting in oscillatory transients in the electrical supply, eg when capacitors are switched, also contribute substantially to power quality disturbances. The most significant and critical power quality problems are, however, voltage sags or complete interruptions of the energy supply [1].

The CBEMA curve published by Technical Committee 3 (TC3) of the Information Technology Industry Council, formerly known as the Computer & Business Equipment Manufacturers Association **1**, indicates the magnitude and duration of undesired events and is widely used by industry to measure the performance of all types of equipment and power systems. Points below the envelope will cause the load to drop out, while points above the curve can cause other equipment malfunctions, such as insulation failures, overvoltage trip or overexcitation. The CBEMA curve is a standard design target for all sensitive equipment intended to be operated on the power grid.

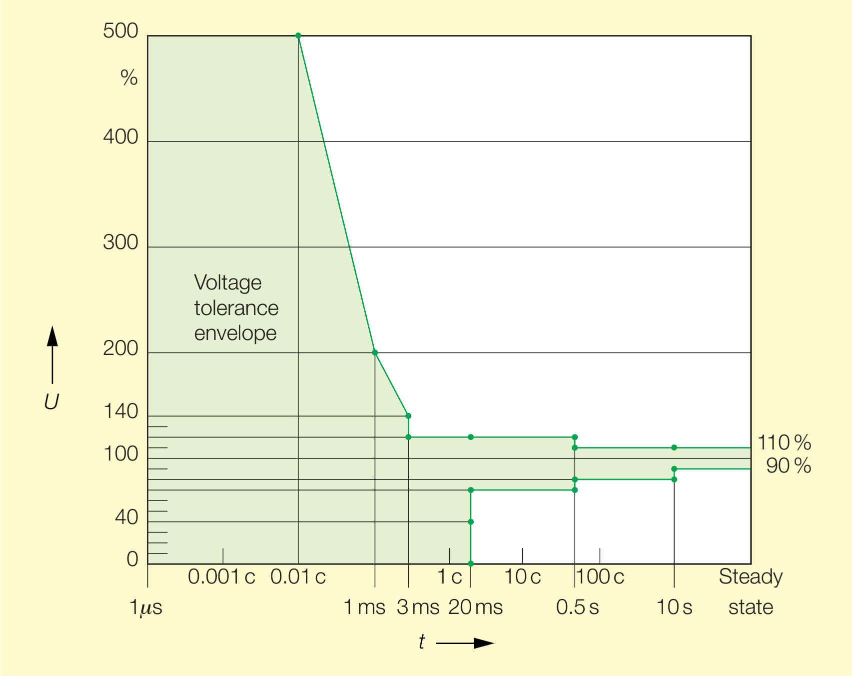
IEEE Standards Coordinating Committee 22 (Power Quality) as well as other international committees recommend that the following technical terms be used to describe main power quality disturbances 2:

**Sags**

A decrease in rms voltage or current at power frequency for durations of 0.5 cycles to 1 minute. A voltage sag to 10 % means that the line voltage is reduced to 10 % of the nominal value. Typical values are 0.1 to 0.9 pu.

**Interruptions**

The complete loss of voltage (below 0.1 pu) on one or more phase conductors for a certain period of time. Momentary interruptions are defined as lasting between 0.5 cycles and 3 s, temporary interruptions have a time span between 3 s and 60 s, and sustained interruptions last for a period longer than 60 s.




***The CBEMA curve indicates the magnitude and duration of voltage tolerances for all types of equipment. It is used widely in industry for performance measurements.*** 1

*U Voltage*

*t Time in cycles (c) and seconds (s)*

**Swells**

A temporary increase in rms voltage or current of more than 10 % of the nominal value at power system frequency which lasts from 0.5 cycles to 1 minute. Typical rms values are 1.1 to 1.8 pu.

**Transients**

These pertain to or designate a phenomena or quantity varying between two consecutive steady states during a time interval which is short compared with the time scale of interest. A transient can be a unidirectional impulse of either polarity, or a damped oscillatory wave with the first peak occurring in either polarity.

**Overvoltage**

When used to describe a specific type of long-duration variation, this refers to a voltage having a value greater than the nominal voltage for a period of time greater than 1 minute. Typical values are 1.1 to 1.2 pu.

**Undervoltage**

Refers to a voltage having a value less than the nominal voltage for a period of time greater than one minute. Typical values are 0.8 to 0.9 pu.

***The most significant waveform distortions associated with poor power quality*** 2

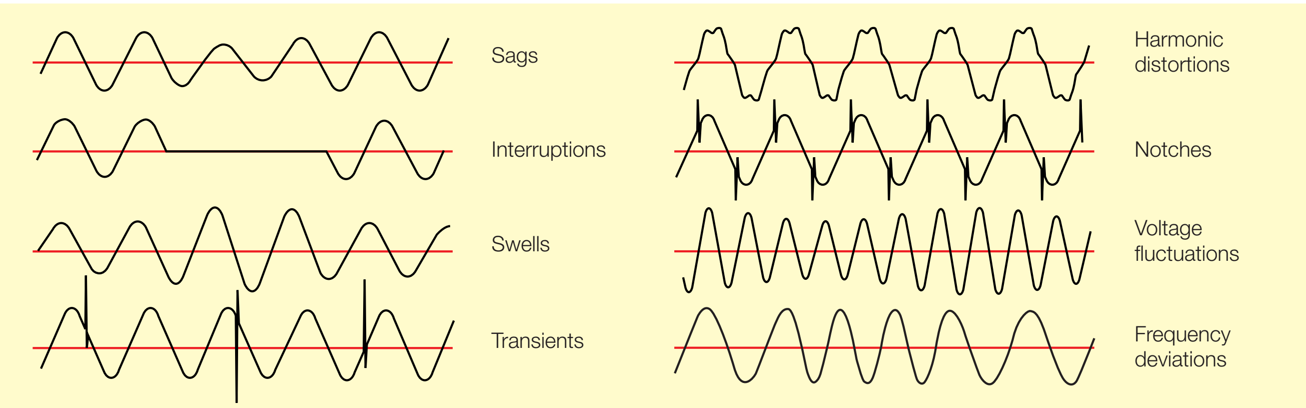


**Table 1:**
**Power quality problems and available mitigation devices**

| *Mitigation devices* | *Sags* | *Interruptions* | *Swells* | *Transients* | *Overvoltage* | *Undervoltage* | *Harmonics* | *Notches* | *Voltage fluctuations* |
|---|---|---|---|---|---|---|---|---|---|
| SA | | | | ✓ | | | | | |
| BESS | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ |
| DSTATCOM | | | | ✓ | ✓ | ✓ | | | ✓ |
| DSC | | | | | | ✓ | | | ✓ |
| DVR | ✓ | | ✓ | ✓ | | | ✓ | | ✓ |
| PFCC | | | | | ✓ | ✓ | | | |
| SMES | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ |
| SETC | ✓ | | ✓ | | ✓ | ✓ | | | |
| SSTS | ✓ | ✓ | ✓ | | | | | | |
| SSCB | | ✓ | | | | | | | |
| SVC | ✓ | | ✓ | | ✓ | ✓ | | | ✓ |
| TSC | | | | ✓ | | ✓ | | | |
| UPS | ✓ | ✓ | ✓ | | ✓ | ✓ | | | |
| APF(TF) | | | | ✓ | | | ✓ | ✓ | |

APF(TF) = Active power filter or tuned filter
BESS = Battery energy storage system
DSTATCOM = Distribution static synchronous compensator
DSC = Distribution series capacitor
DVR = Dynamic voltage restorer
PFCC = Power factor correction capacitor
SA = Surge arrester
SMES = Superconducting magnetic energy storage system
SETC = Static electronic tap changer
SSTS = Solid-state transfer switch
SSCB = Solid-state circuit-breaker
SVC = Static var compensator
TSC = Thyristor switched capacitor
UPS = Uninterruptible power supply

**Harmonics**

Sinusoidal voltages or currents having frequencies that are multiples of the fundamental power frequency. Distorted waveforms can be decomposed into a sum of the fundamental frequency wave and the harmonics caused by nonlinear characteristics of power system devices and loads.

**Table 2:**
**Customers with sensitive or critical processes**

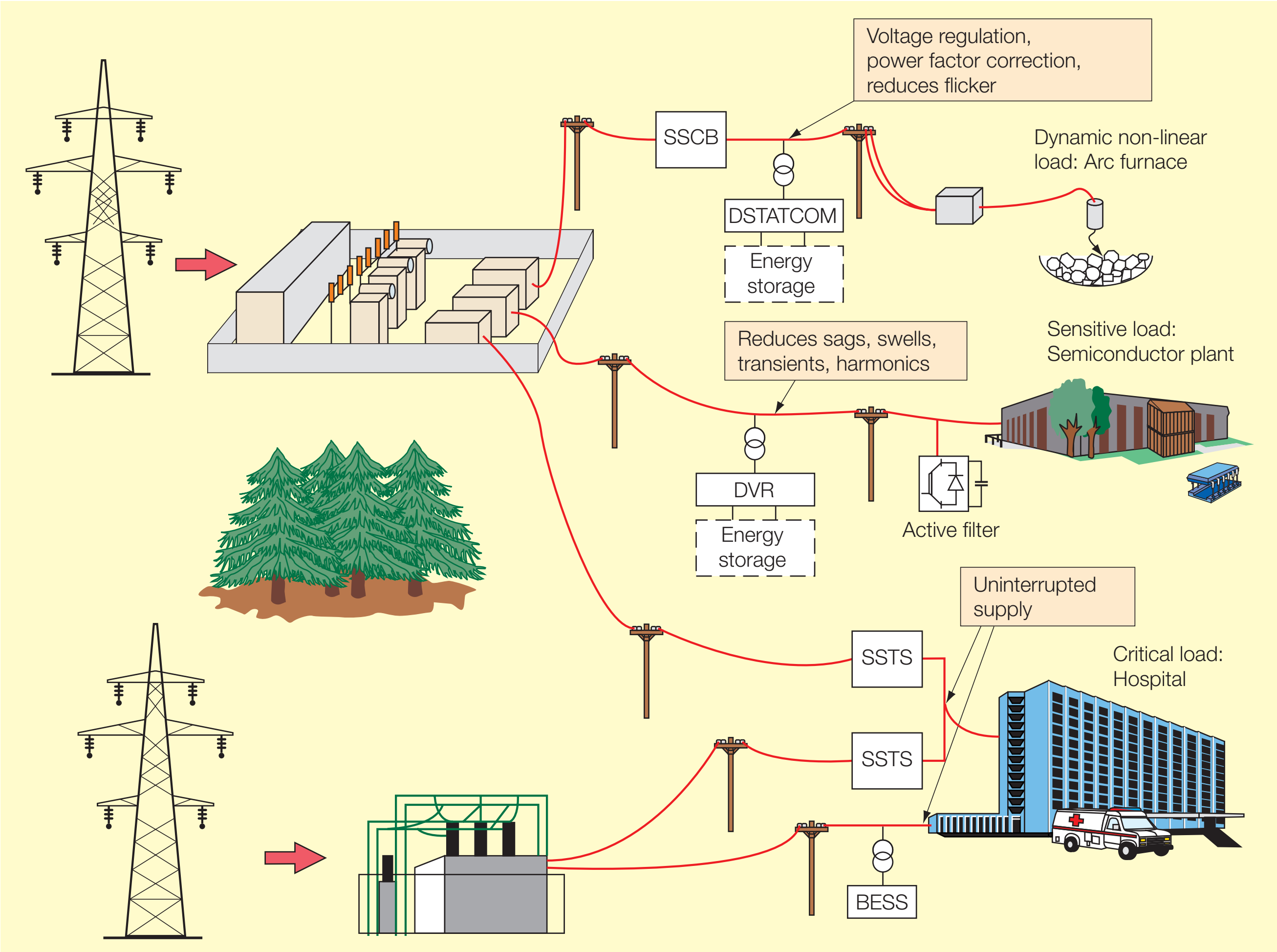
| *Industry segment* | *Industrial process* |
|---|---|
| Continuous process | Paper, fiber and textile factories<br>Plastics extruding or moulding plants |
| Precision machining | Automobile parts manufacturing<br>Large pump forging factories |
| High-technology products and research | Semiconductor manufacturing<br>Particle physics research centers |
| Information technology | Data processing centers<br>Banks<br>Telecommunications<br>Broadcasting |
| Safety and security related | Hazardous process<br>Chemical processing<br>Hospitals and health care facilities<br>Military installations<br>Power plant auxiliaries<br>Large transmission substations |

**Interharmonics**

Voltages and currents having frequencies that are not integer multiples of the fundamental power frequency. Interharmonics are mainly caused by static frequency converters, cycloconverters, induction motors and arcing devices, and can have the effect of inducing visual flicker on display units. Power line carrier signals are also considered as interharmonics.

**Notches**

Periodic voltage disturbances lasting less than 0.5 cycles. Notching is caused mainly by power electronics devices when the current is commutated from one phase to another during the momentary short circuit between the two participating phases. Frequency components associated with notching can therefore be very high, and measuring with harmonic analysis equipment may be difficult.




***Innovative ABB power quality mitigation devices*** **3**

| | | | |
|---|---|---|---|
| BESS | *Battery Energy Storage System* | DVR | *Dynamic Voltage Restorer* |
| DSTATCOM | *Distribution Static Synchronous Compensator* | SSCB | *Solid-State Circuit-Breaker* |
| SSTS | *Solid-State Transfer Switch* | | |

**Voltage fluctuations**

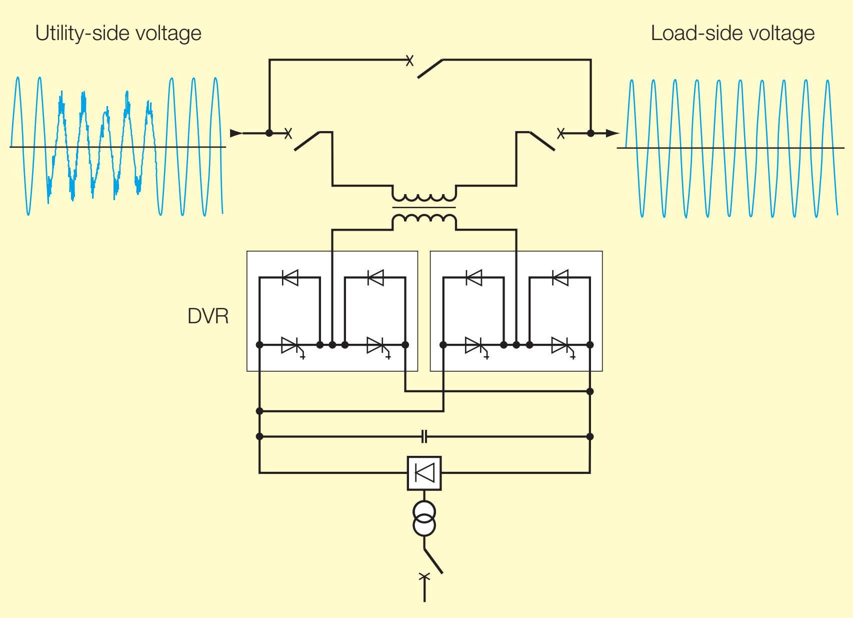
Voltage fluctuations are systematic variations in the envelope or a series of random voltage changes with a magnitude which does not normally exceed the voltage range of 0.9 to 1.1 pu. Such voltage variations are often referred to as flicker. The term flicker is derived from the visible impact of voltage fluctuations on lamps. Among the most common causes of voltage flicker in transmission and distribution systems are arc furnaces.

**Innovative and conventional technologies for the mitigation of power quality problems**

There are two general approaches to the mitigation of power quality problems. One, termed load conditioning, is to ensure that the process equipment is less sensitive to disturbances, allowing it to ride through the disturbances. The other is to install a line conditioning device that suppresses or counteracts the disturbances.

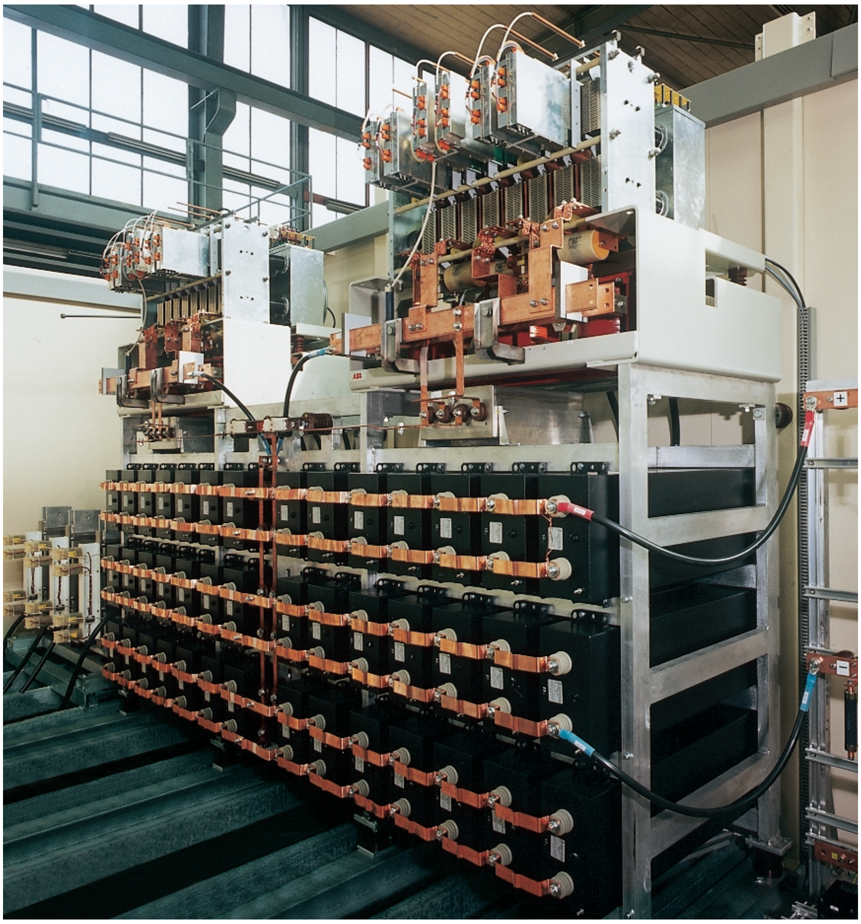
Commercially available mitigation devices tend to protect against a group of power quality disturbances. Mitigation devices vary in size and can be installed at all voltage levels of a power system (HV, MV and LV). The mitigation device and point of connection is chosen according to its economic feasibility and the reliability that is required. Innovative solutions employing power electronics **3** are often applied when rapid response is essential for suppressing or counteracting the disturbances, while conventional devices (eg, switched capacitor banks) are well suited for steady-state voltage regulation. An overview of the power quality problem areas and their possible solutions is given in *Table 1*.

For simple load applications, selection of the proper mitigation device is fairly straightforward. However, in large systems with many loads all aspects of the power system must be considered carefully. Also, when dealing with large systems it is




*Mitigation of voltage sags with the Dynamic Voltage Restorer (DVR)* **4**

*State-of-the-art IGCT-based voltage source converters of a DVR mounted on capacitor banks* **5**



necessary to know the different sensitive load requirements. Furthermore, consideration must be given to the potential interaction between mitigation devices, connected loads and the power system [2].

### Application and examples of power quality devices

Poor power quality can cause unscheduled shutdown of industrial processes or equipment failure, resulting in substantial costs for customers. The industries affected are many and varied. A list of some of the industrial segments and related processes that are prone to power quality disturbances is given in *Table 2*.

### Voltage sag mitigation with a dynamic voltage restorer

Semiconductor manufacturing plants have sensitive equipment that can be shut down or may be disturbed by momentary sags of the supply voltage due to faults on the utility side. To ensure that the production process is not interrupted during sags, a power quality device, such as the Dynamic Voltage Restorer (DVR), can be installed to mitigate this problem [3]. As shown in **4**, the DVR can respond within sub-cycles to a fault on the utility side, in effect shielding the customer from the fault.

To be able to mitigate voltage sag, the DVR must be capable of rapid control response and feature both an energy source and transformer for coupling the boosting voltages that provide the compensation.

The key components of the DVR **4** are:

- Switchgear
- Booster transformer
- Harmonic filter
- Two IGCT voltage source converters
- DC charging unit
- Control and protection system
- Energy source, eg a storage capacitor bank

As long as the power supply conditions remain normal the DVR operates in low-loss standby mode, with the converter side of the booster transformer shorted. Since no voltage source converter (VSC) modulation takes place, the DVR produces only conduction losses. Use of Integrated Gate Commutated Thyristor (IGCT) technology minimizes these losses [4].

When a voltage sag (or swell) occurs on the line side, the DVR responds by injecting three single-phase AC voltages in series with the incoming three-phase network voltages, compensating for the difference between faulted and prefault voltages. Each phase of the injected voltages can be controlled independently (ie, their magnitude and angle). Active and reactive powers required for generating these voltages are supplied by two pulse-width modulated (PWM) voltage source converters fed from a DC link as shown in **5**.

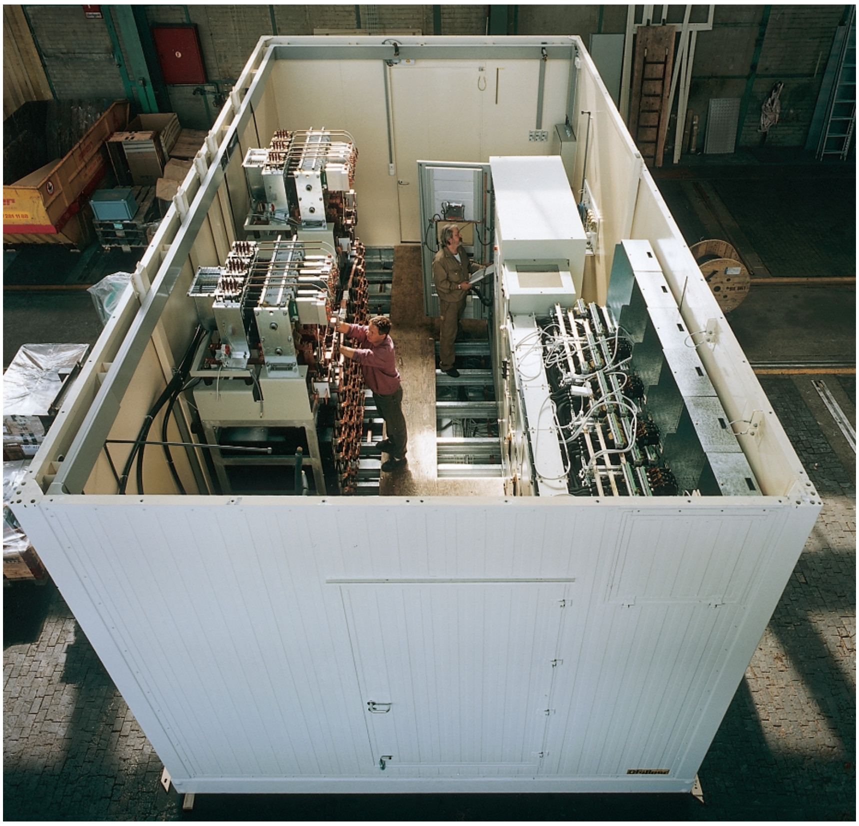
A medium-voltage, container-based DVR installation for a 4-MVA load **6** provides further flexibility by facilitating relocation and therefore maximum utilization of the investment.

To ensure that the DVR is capable of meeting the specified requirements, its dynamic performance and the control system functions must be verified using a real-time analogue simulator. The control system is a replica of the one to be used in the customer's installation.

The voltages on the network and load sides for a simulated 38 % voltage sag are shown in **7**. The sag occurs at the instant the voltage peaks on one phase. The fault is cleared by the system protection after three cycles, with the supply voltages recovering to prefault levels. The DVR then returns to its standby operating mode. The load-side voltages remain at prefault levels for the duration of the fault, highlighting the rapid control response of the DVR. Good agreement between the calculated voltage values and the assessment carried out with a hardware-based model provide further verification of the system's design and performance.

### Flicker compensation and energy supply with DSTATCOM

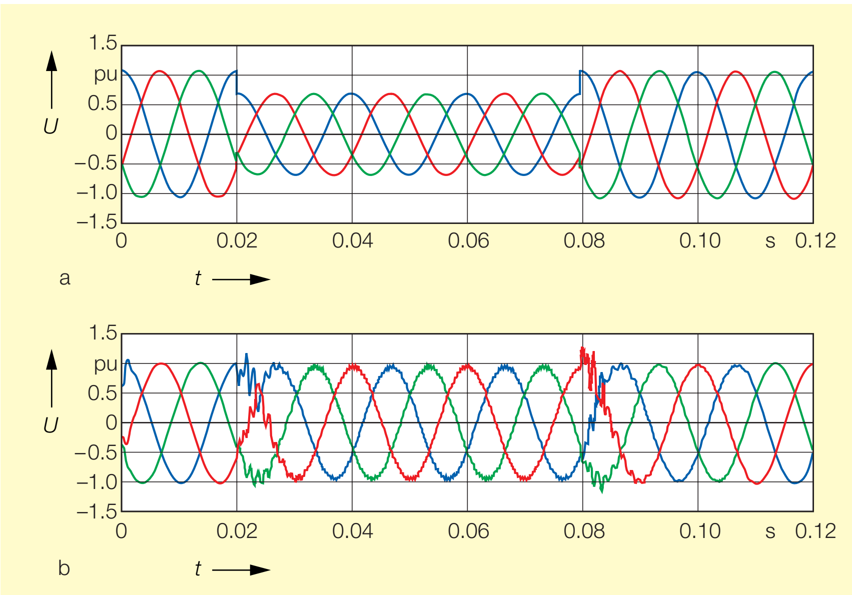
The DSTATCOM is a shunt-connected device based on pulse-width modulated (PWM) voltage source converters. Accord-

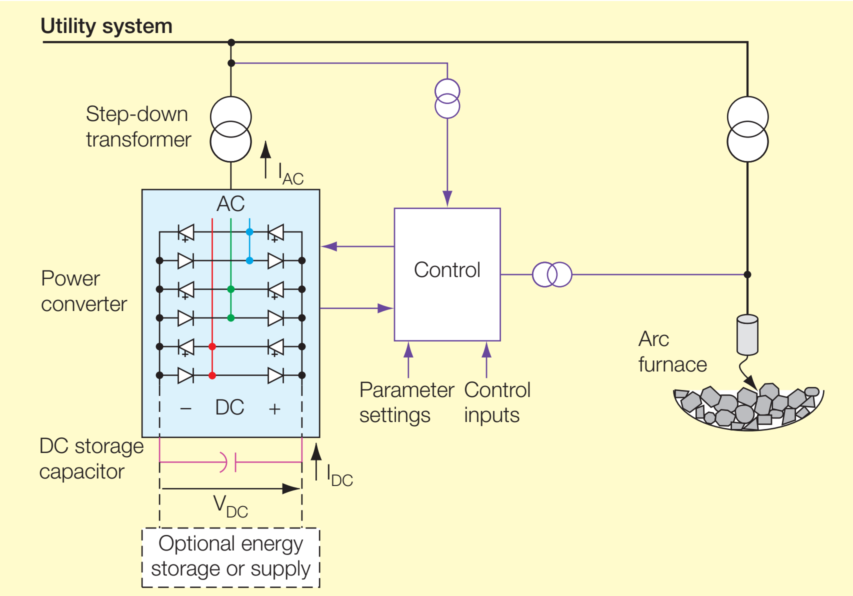


***Container-based DVR guaranteeing a reliable supply and enhanced power quality for a 4-MVA semiconductor manufacturing plant*** **6**

***Calculated per-unit voltages on the network (a) and load side (b) during a three-phase voltage sag, with the DVR in operation*** **7**

*U* *Input (a) and output (b) voltage of DVR*
*t* *Time*






***Arc furnace load compensation by means of a distribution static synchronous compensator (DSTATCOM)*** **8**

ingly, it replaces conventional voltage and reactive power control elements. It can improve the voltage profile along feeders, reduce losses and is also capable of compensating for real power fluctuations on account of the presence of an energy storage system connected to the DC side.

Under normal power supply conditions, the DSTATCOM operates as a reactive power source or in low-loss standby mode. When voltage fluctuations occur, the DSTATCOM responds by injecting currents with the proper phase angle and magnitude.

The non-linear nature of arc furnace loads has a substantial influence on the quality of the power supply. Power fluctuations due to arc furnace operation cause unwanted, visible voltage flicker effects. The DSTATCOM solution shown in **8** can be applied to restore power quality in such situations. A DSTATCOM is able to meet the demanding flicker attenuation requirements with a response of an order of magnitude faster than with more conventional devices. Furthermore, the DSTATCOM does not contribute to resonant interaction in the AC system.

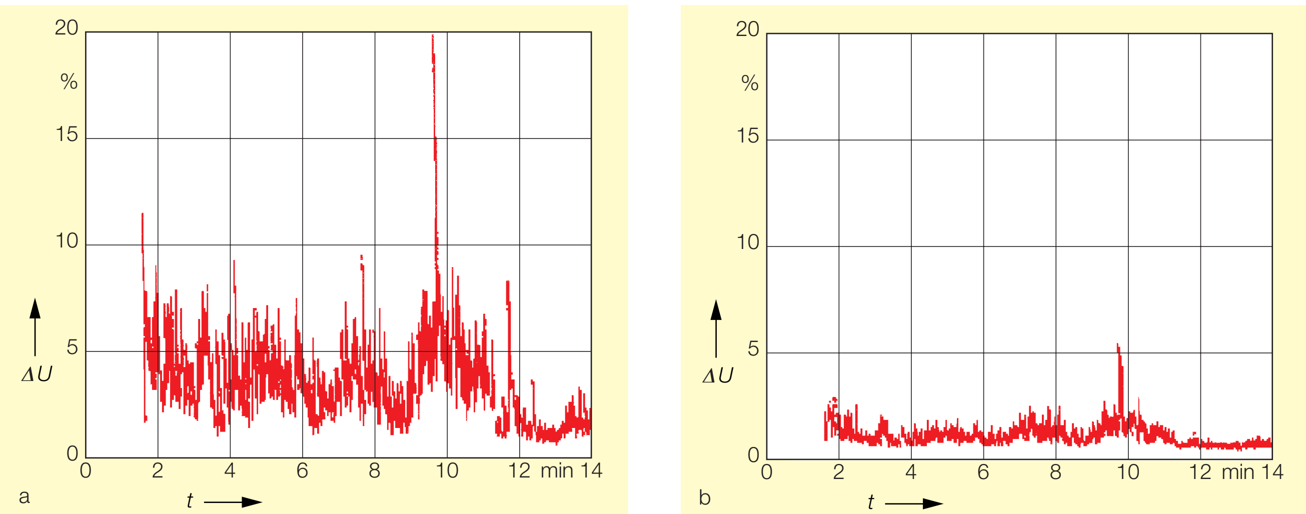
Flicker recordings of an arc furnace load that show the effect of using a DSTATCOM are given in **9**. It can be seen that the variations in voltage are effectively attenuated when a DSTATCOM is installed.

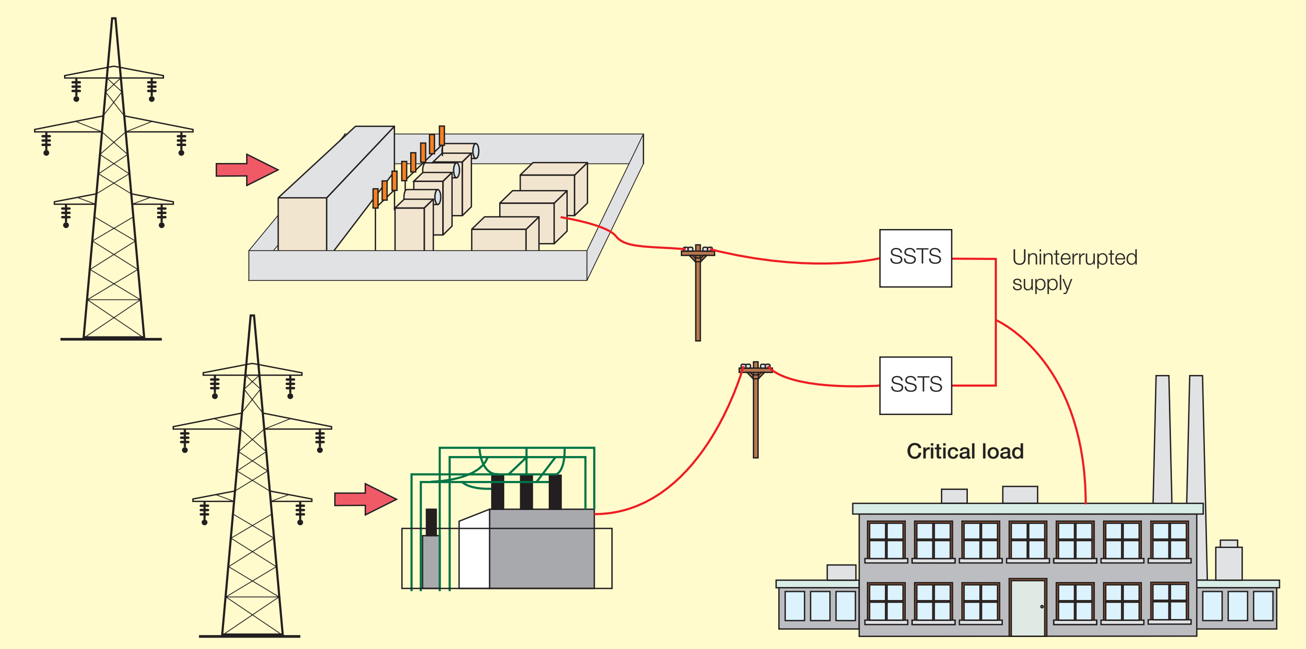
A DSTATCOM coupled with a Solid-State Circuit-Breaker (SSCB) and an energy storage system (eg, BESS), is also advantageous. If an SSCB is installed between the incoming supply and the critical load bus, and a DSTATCOM equipped with an energy storage system such as BESS is operated in parallel on the load bus, full support can be provided during temporary supply interruptions. The SSCB immediately isolates the critical load from the fault and the DSTATCOM supports the load with energy from the storage system.

***Flicker (voltage variations) associated with arc furnace operation*** **9**

a *Without mitigation device*
b *With DSTATCOM*

*ΔU* *Voltage variation*
*t* *Time*






*Mitigation of momentary, temporary and sustained supply interruptions by a solid-state transfer switch (SSTS)* **10**

### Solid-state transfer switch for mitigation of supply interruptions

The Solid-State Transfer Switch (SSTS) is designed to replace the mechanical auto-transfer equipment currently used to switch major industrial and commercial facilities from one feeder to another – a process that typically takes 0.5 to several seconds. An SSTS can also provide companies with a cost-effective alternative to an inhouse uninterruptible power supply system.

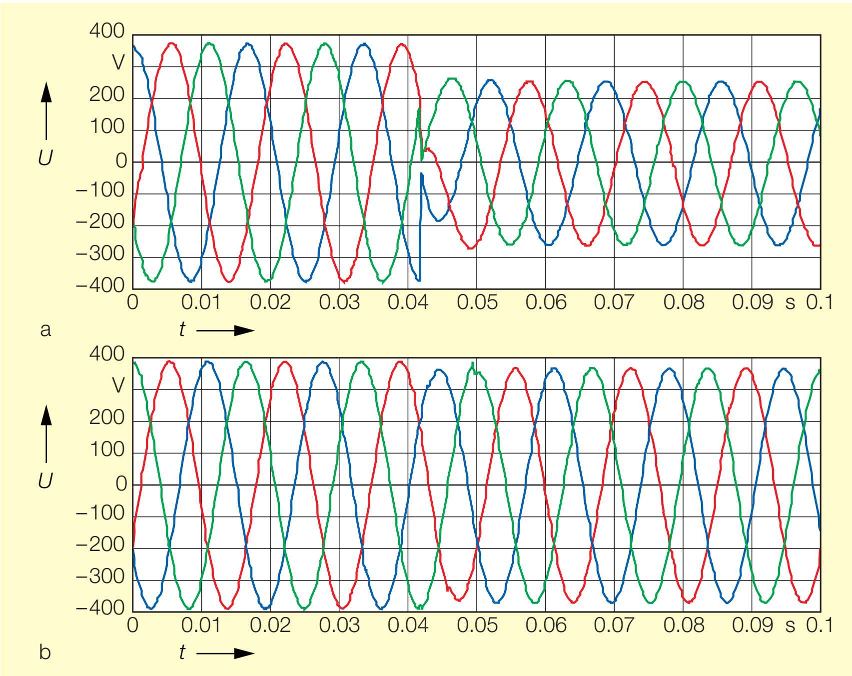
A typical application for an SSTS in a utility-provided power quality solution is shown in **10**. A sensitive consumer is fed via a radial line by a utility operating an isolated medium-voltage network. In the event of disturbances in the supply network an attempt is made to clear the fault through auto-reclosure. However, the brief interruption of supply power would be sufficient to trip the consumer's equipment, resulting in production downtime. A secondary independent feeder with sufficient capacity is available in parallel with the primary line. If auto-reclosure is initiated in the medium-voltage network, the SSTS will immediately transfer the sensitive load to the secondary supply.

During normal operation, the switch connected to the primary feeder is kept closed and the switch on the secondary feeder is kept open. If a disturbance such as a voltage sag, short-circuit or outage occurs on the primary line, the load is transferred to the secondary feeder within milliseconds.

In order for the SSTS to be effective, the distribution system in which it is to be installed has to meet certain requirements:

*Primary (a) and load feeder (b) voltages in the case of a system fault* **11**

*U* Voltage
*t* Time



- Two feeders from different substations
- Spare distribution capacity in the back-up feeder
- Spare distribution capacity in the substation
- Reliable transmission with good power quality

Curves obtained from computer simulation of the SSTS 11 show the voltages of the primary load feeder and the load bus during a three-phase fault. Transfer of the load from the faulted feeder to the secondary feeder occurs immediately and with no adverse effect on the load.

### Metal oxide surge arresters for transient overvoltage protection

Protection against transient overvoltages due to lightning strikes or switching of equipment plays an important role in improving the quality of the power supply.

Modern metal oxide surge arresters 12 reduce the transient overvoltages to under 1.5 per unit of the rated system voltage. They are therefore ideal for transient overvoltage limitation in transmission and distribution systems, and make an important contribution to power quality enhancement for both the high and the low voltage ranges [5].

### Innovative system solutions – the key to cost-effective power quality enhancement

High power quality requires the physical characteristics of the electrical supply under normal operating conditions to neither disrupt nor disturb the customers' processes. Increasingly, national and international standards are adopted which describe levels which are acceptable for different types of disturbances in the electrical supply.

Statistics show that the disturbances causing the most frequent process outages, and hence substantial economic losses, are sags and interruptions. Concern about power quality is being driven by the deterioration of power quality levels as a result of deregulation, more sensitive loads, and the increase in processes based on power electronics.

***POLIM® medium-voltage surge arresters for transient overvoltage protection*** 12

IGCTs have been chosen for the voltage source converters used in the ABB power quality solutions described. These newly developed power electronics devices unite the benefits of Gate Turn-Off (GTO) thyristors with the strengths of the Insulated Gate Bipolar Transistor (IGBT). The IGCT has the advantage of low losses when conducting like a thyristor and the excellent switching capabilities of an IGBT. IGCT-based converters are available for a wide range of powers from 0.5 MW to 100 MW with series-connected devices. In addition, IGCTs ensure:

- High converter reliability due to the use of a small number of field-proven components (MTBF ≥ 20 years).
- High converter efficiency in steady state operation. The total converter losses are only a very small fraction of the equipment rating.
- Inherent safety: even under worst-case conditions IGCTs will not open, but short the circuit, and are able to conduct currents far in excess of expected fault levels.

Power quality issues will become an increasingly important factor in the global economy. ABB High Voltage Technologies is well placed to provide power quality mitigation system solutions that address these issues cost-effectively through the use of innovative technologies.

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### Authors' address


Arun Arora
Kevin Chan
Thomas Jauch
Alexander Kara
Ernst Wirth
ABB High Voltage Technologies Ltd
P.O. box 8546
CH-8050 Zurich
Telefax: +41 1 318 1724
E-mail:
arun.arora@chhos.mail.abb.com
kevin.chan@chhos.mail.abb.com
thomas.jauch@chhos.mail.abb.com
alexander.kara@chhos.mail.abb.com
ernst.wirth@chhos.mail.abb.com

# PQ-SMART™ – a simulation tool for power quality modelling and analysis

**PQ-SMART™ is a power systems engineering tool which combines off-the-shelf software products in a way that makes it suitable for users with different technical backgrounds. The design philosophy behind PQ-SMART, which stands for Power Quality Simulation, Monitoring And Relay Testing, was to re-use software products already in existence and widely used within the ABB Group. This resulted in the choice of MATLAB, EMTP and the Windows-based PC platform. The tool is designed for use in the analysis and modelling of power quality problems in electricity grids.**

While many user-friendly software tools are available today for scientific computing and power system simulation, there is still no tool that caters to the specific needs of power quality modelling and analysis. Such a tool must be easy to use and must generate time-domain waveforms similar to those recorded in the real world.

### Power quality simulation at the present time

A variety of user-friendly software tools are available today for studying the steady-state behaviour of power networks in terms of their power quality. While they allow, for example, the magnitude of voltage sags to be studied, steady-state models are inadequate when it comes to determining the duration of the sags. The same is true when users want to include the behaviour of complex devices, such as arc furnaces, electric drives, surge arresters, etc, in the system model. Another deficiency of steady-state tools is that they do not allow the operation of protective and monitoring algorithms embedded in microprocessor-based devices to be verified or tested.

The ElectroMagnetic Transients Program (EMTP) is used extensively by power engineers to study the transient behaviour of electrical systems. A major problem with EMTP (and its variations), however, is that it is difficult and time consuming to set up a case. Even the task of modifying an existing file to generate new simulation cases requires some level of expertise. As a result, the EMTP development group (Development Coordination Group, or DCG), a consortium of utility and industrial organizations, is planning to make the EMTP more user-friendly by adding a graphic interface; however, this new feature has not yet been made available.

**Khoi Vu**
**Le Tang**
**Kevin J. Timko**
ABB Power T&D Company Inc

**Damir Novosel**
ABB T&D Technology Ltd

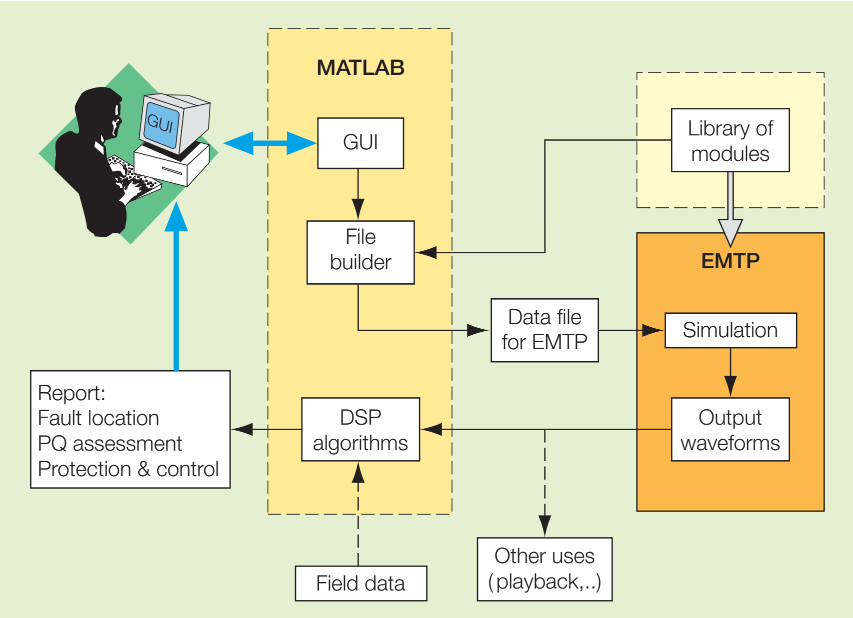
**Harri Kuisti**
**Tapio Hakola**
ABB Transmit Oy

An alternative to EMTP is EMTDC, which uses similar computing methods but is accompanied by a graphic interface (PSCAD). The two software packages are not compatible as the input and output files from one tool cannot be processed by the other. Even though EMTDC is more recent and has some catching up to do in some areas of modelling and computing, its graphic interface has made it the natural choice for first-time users. Each tool comes with its own library of models representing basic power circuit components. The user chooses components, specifies their parameters and assembles them (via text lines for EMTP, and graphics for EMTDC) to build a system. The standard library is somewhat limited, yet sufficient for normal use. In cases of simulation involving more complex devices and/or devices which are still at the development stage, expertise is needed to build detailed circuits. In such situations, building a model is not simply a matter of piecing together existing blocks or routine coding of a set of mathematical equations; rather, the process requires an understanding of the physical device, ad-hoc methods of avoiding numerical instability, and particularly the time-consuming task of validating the model.

More generic simulation software packages, such as SPICE, SABER, and MATLAB (with its companion SIMULINK) can also be used for power system simulation. However, these tools are not tailor-made for power system models, and therefore the time needed to set up a realistic system makes them impractical.

### The organizational perspective

At ABB, as in other large organizations, computer simulation and studies as well as product development are carried out on a




***Architecture of PQ-SMART. The software tool combines the simulation and modelling capabilities of the ElectroMagnetic Transients Program (EMTP) and the data processing and analytical tools in MATLAB.*** **1**

DSP *Digital signal processing*

GUI *Graphic user interface*

large scale. A range of software tools is purchased, and essentially a different tool is used for each different activity. Engineers sometimes write new software codes if there is no suitable tool commercially available. The co-existence of many different tools is obviously a cost factor; this applies particularly to the maintenance of the different programs and the training of new users. Efforts are being made to reduce the number of software tools to a minimum. Although it is impractical to think in terms of a 'unified' tool capable of satisfying every engineer's needs, a tool that can cater to a large group of engineers is feasible.

Recognizing that EMTP has been the industry standard for over 20 years, and that significant and valuable work has already been carried out in the area of power system component modelling, a team at ABB decided to build a new simulation tool based on EMTP. The tool is designed to run on personal computers. Basically, it relies on an extensive library of EMTP modules, each module being a parameter-based description of a particular power system component (eg, transformer, load, motor and rectifier). This library represents the heart of the simulation tool, as it directly influences how realistic the simulation results will be.

## Description and applications of the software tool

The software tool was originally intended to be used to simulate and analyze power quality in distribution systems. It has been named PQ-SMART, for Power Quality Simulation, Monitoring And Relay Testing. Unlike competing tools for power quality study that rely on steady-state methods, PQ-SMART allows simulation in the time domain.

The tool combines the simulation and modelling capabilities of EMTP with the data processing and analytical tools in MATLAB. Communication between EMTP and MATLAB is via the data input and output files **1**.

The three main elements of the tool are:

- EMTP model library
- MATLAB-based graphic user interface (GUI)
- MATLAB-based output post-processing/analysis facilities

Each element of the model library is represented graphically by a custom-designed icon. Using the computer's mouse, the user can assemble icons to build the single-line diagram of a power network. The program compiles the user's input and starts the simulation automatically. Retrieval of simulated waveforms (voltages and currents) is achieved by clicking on icons designated as 'sensors'.

A number of menus allow the user to apply power quality analysis functions to the observed waveforms. The list includes not only functions being used in the power quality field, but also new functions that have potential applications. Most importantly, the analysis package allows the user to 'plug and play' his own algorithms. This flexibility is of great value to the product development process because the engineer can quickly evaluate and fine-tune a particular algorithm.

PQ-SMART can also be used to support equipment testing – a procedure in which the simulated voltages and currents are sent to a test apparatus via power amplifiers. The user can run a large number of cases and evaluate the performance of the apparatus under simulated conditions. For example, a harmonic analyzer can be tested and its results compared with the output of the MATLAB-based routines.

In another application for PQ-SMART, its DSP package can be used to post-process recorded field data. In this case, the user bypasses the EMTP simulation and imports the data directly into MATLAB. The DSP package contains MATLAB's factory-built as well as user-written functions.

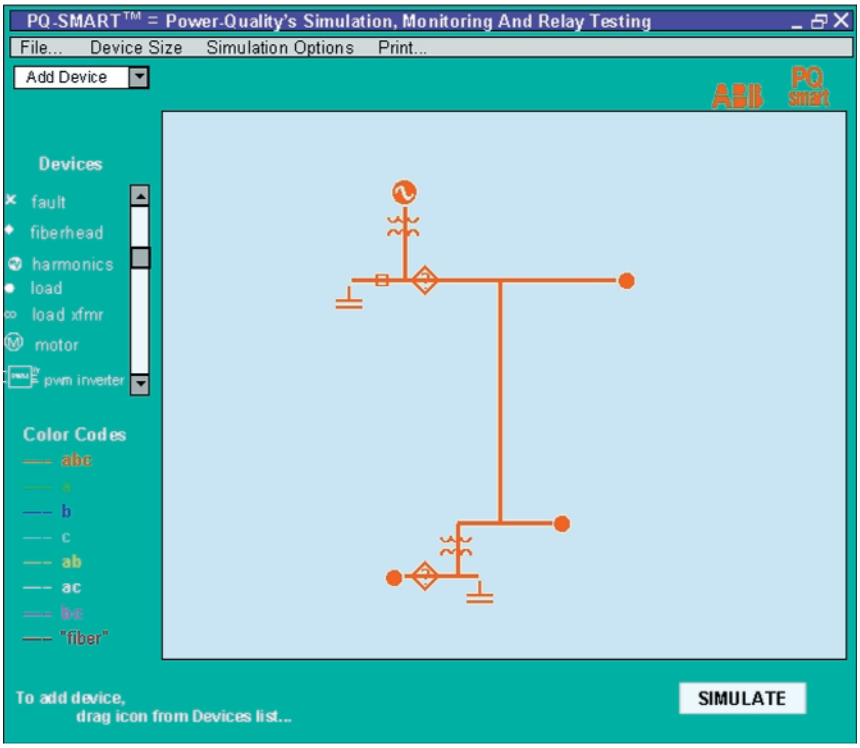
## EMTP-based component library

The EMTP data module feature has been used extensively to simplify the use of the basic equipment models and to extend the modelling capabilities to more complex equipment models. The model library developed for this purpose relies heavily on the enhanced features of version 3.0 of EMTP (EMTP96).

The modules that have been developed to date include:

- Line models
- Transformer models
- Breaker/switch models
- Source/equivalent models
- Harmonic source and filter models
- Load models
- Protection models
- Power electronics models (rectifiers, inverters, etc)
- Sensor models
- Shunt and series capacitor bank models
- Fault models (impedance-based faults and arcing faults)

The component library is still growing. Every time a new module is needed, it is built, tested and validated by an EMTP expert. A written description of the module is prepared and stored in a database for future reference. By using a set of MATLAB-based programs, the design team can link this module to PQ-SMART.




***Single-line system diagram via which the user interacts with PQ-SMART*** **2**

### MATLAB-based graphic user interface

Interaction between the user and PQ-SMART is strictly via the graphic user interface, or GUI. The GUI consists of many windows, the main one being the single-line diagram. A simple example of a single-line diagram is shown in **2**. Colours are used to denote multi- and single-phase feeders (lines). The user can zoom in/out, draw and reshape lines, add or remove devices, etc.

To inspect, assign or change parameters of a particular component, the user double-clicks on the device icon. This action opens a parameter window belonging to the second level in the GUI hierarchy. The complexity of a parameter window varies from one component to another. For example, a capacitor bank is fairly simple (the parameters being the voltage and var ratings), and its window contains only 'edit' boxes which the user has to fill in. In contrast, a meaningful window for a rectifier requires the display of a detailed circuit with diodes, thyristors, resistors, etc. A complex window, for example, has several lower-level windows hidden beneath it, and can be opened one by one for parameter input.

The general appearance of each parameter window is fixed (ie, its appearance cannot be changed by the end-user) and is composed of a variety of graphic objects allowed by MATLAB. These graphic objects include `text`, `axes`, `line`, `menu`, and `uicontrol`. Sometimes 'special effects' are embedded to help the user visualize his actions. For example, the window for 'harmonic source' automatically computes and displays the injected current based on the harmonic amplitude and phase angles that the user specifies. In this way, the user can 'see' the injected waveform, and can make necessary adjustments before invoking the time-domain simulation.

### MATLAB-based post-processor of signals

In addition to the EMTP library and the set of GUI windows, the tool contains utilities that allow post-processing of signals generated during an EMTP simulation. However, the post-processing feature is not restricted to EMTP-generated signals; field-recorded signals can also be processed after a data conversion.

With a double-click of the mouse button on a sensor icon, the voltages and currents recorded at the sensor's location are fetched and plotted on the screen. The user can zoom in on any portion of the waveform and apply a number of analysis functions to the displayed time window.

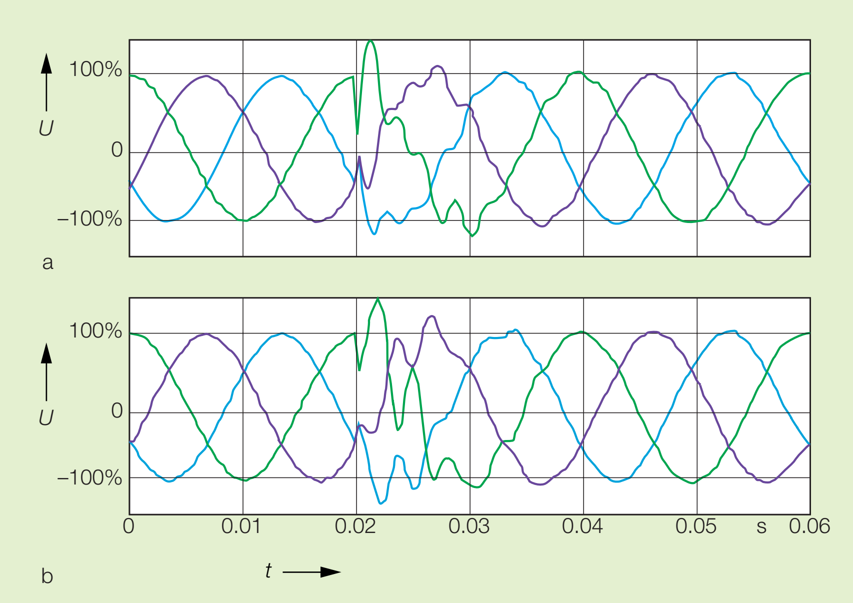
#### Power spectral density

This function employs the FFT (Fast Fourier Transform, a built-in MATLAB funtion) in the calculation of the power spectrum of the signal. The spectrum can be computed using all the data points, or just a selected window of data points; the choice is up to the user, who can zoom in or out of a section of the waveform.

The total harmonic distortion (THD) is also computed for each phase and displayed on the graph automatically:

$$\mathrm{THD} = \frac{\sqrt{A_2^2 + A_3^2 + \ldots + A_n^2}}{A_1} \qquad (1)$$

$A_{1\text{-}n}$ Harmonic amplitudes found by the FFT method




***Magnification of capacitor-switching transients in the distribution network in 2*** **3**

*Voltage (U) on capacitor bus (a) and remote bus (b) when 3-MVA substation capacitor is switched on at time t = 0.02s*

### Voltage imbalance

The voltage imbalance (VI) is defined as the ratio between the negative- and positive-sequence voltages:

$$\mathrm{VI} = \left|\frac{\underline{V}_2}{\underline{V}_1}\right| = \left|\frac{\underline{V}_a + (\underline{V}_b \cdot 1\angle 240°) + (\underline{V}_c \cdot 1\angle 120°)}{\underline{V}_a + (\underline{V}_b \cdot 1\angle 120°) + (\underline{V}_c \cdot 1\angle 240°)}\right| \quad (2)$$

$V_a, V_b, V_c$ Voltage phasors of the three phases a, b and c (the phase sequence is abc). The method for calculating the phasor based on data samples of the waveform is a standard one.

Voltage imbalance can be represented statistically in terms of cumulative probability and probability density. The cumulative $F(x)$ = Pr(VI ≤ $x$) refers to the percentage of observation time that the imbalance VI is below a given level $x$. The probability density function is $f(x) = dF/dx$.

### Voltage sag/swell

Voltage sags and swells refer to rapid deviation of the voltage amplitude from its nominal value. A voltage is considered acceptable if its amplitude falls within a prescribed range.

The analysis function performs the following tasks in connection with voltage sag/swell:

- Tracking and displaying of the signal amplitude as a function of time.
- Sag level versus duration characteristic. Each point on the characteristic represents the magnitude of the sag and the time duration over which the magnitude stays below that level. Such a characteristic is superimposed on an industry standard such as CBEMA. If the sag level versus duration characteristic crosses the acceptable boundaries specified by the standard, then the underlying voltage disturbance can be declared as violating the standard; otherwise, the disturbance is tolerable.

### 'Test your own algorithm'

The analysis functions listed in the three preceding subsections are typical in a power quality assessment. However, there are situations in which the user wants to test his own functions or algorithms with the simulated waveform. The menu 'test your own algorithm' is designed to meet this need. Some familiarity with the MATLAB syntax is required. An example is given in the next section.

## Case studies

### Algorithm design and testing

In the case of digital relays, it is common practice for algorithms to first be coded in MATLAB, tested thoroughly and fine-tuned before being implemented on a hardware platform. When PQ-SMART was first conceived in 1996, a major goal was to support algorithm testing (therefore the name 'Relay Testing' in the acronym). To do this, the engineer first builds a power system, specifies disturbances and runs the simulation. Waveforms (voltages and currents) are then retrieved and monitored within so-called 'sensor' windows. A sensor window has a number of menus that allow the user to apply pre-coded analysis functions, such as those described in the previous section. One menu allows the user to 'plug and play' his own MATLAB codes. *Table 1* gives an example of a typical plug-and-play code. Generally, the first few lines (1 through 7) call the function `getWave` to retrieve the time, voltages and currents that are plotted in the sensor window. These data are then applied to a user-defined function, `calcPhasor`, which converts selected waveforms ($v_a$–$v_b$ and $i_a$–$i_b$) into complex-valued phasor representation. Phasor calculations are based on sliding windows, and when there is a disturbance in the waveforms the output experiences a fluctuation. In the case of a short circuit, the DC component in the transients can produce erroneous phasor values and affect the operation of the impedance relays. In this example, the engineer has to design `calcPhasor` so that the output phasors reach their steady-state values as fast as possible. He can fine-tune the algorithm until a certain performance is reached. In the simple example shown (*Table 2*), the performance is evaluated visually by computing and plotting the apparent impedance $z_{App}$.

### Magnification of capacitor-switching transients

Capacitor switching can produce transients and adversely affect the power quality in a network. It is not uncommon to find that transients generated at the switching site are less severe than those at a remote location. This phenomenon was publicized in the late 1980s and has become known as capacitor-switching transients magnification. The distribution network shown in **2** is used for demonstration. The 3-MVAr capacitor in the substation is switched in at time $t$ = 0.02 s, and sensors record the voltages in the substation and at the remote bus. The simulated waveforms are shown in **3**, where the transients in the remote voltages are more severe than those in the voltages at the switching site. (The voltage levels are 13.8 kV and 400 V, respectively.) These waveforms can be further analyzed by applying selected MATLAB built-in functions, and its companion Signal Processing Toolbox.

**Table 1**
**Example of algorithm design and testing.**
`calcPhasor` **is the user-defined function under test.**

```
t    = getWave ('time');                          %  1
v_a  = getWave ('volt', 'a');                     %  2
v_b  = getWave ('volt', 'b');                     %  3
v_c  = getWave ('volt', 'c');                     %  4
i_a  = getWave ('amp', 'a');                      %  5
i_b  = getWave ('amp', 'b');                      %  6
i_c  = getWave ('amp', 'c');                      %  7
%                                                 %  8
dt   = t(2)-t(1);                                 %  9
V_ab = calcPhasor(v_a-v_b,dt,60,1);               % 10
I_ab = calcPhasor(i_a-i_b,dt,60,1);               % 11
z_App = V_ab/I_ab;                                % 12
figure;                                           % 13
plot(z_App)                                       % 14
xlabel('R')                                       % 15
ylabel('X')                                       % 16
  % etc.
  % et cetera
```

### Sag analysis

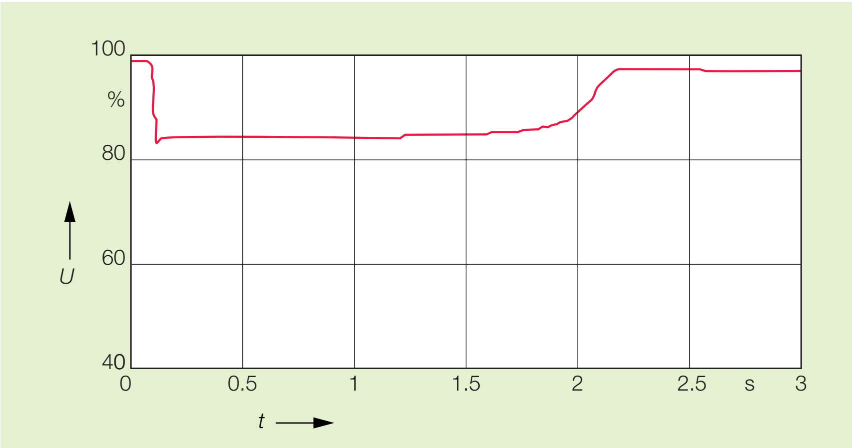
Voltage sags in a distribution network are typically caused by a short circuit (on a distribution feeder or in the transmission system), or by starting of a large motor. Steady-state analyses are commonly performed for voltage sags. While fast and capable of providing some insights, the steady-state approach inherently lacks the time dimension. Time-domain simulation using an EMTP-like computing engine can take into account the dynamics of network components, and therefore can produce the duration of voltage sags realistically. An example of voltage sag due to the starting of a motor is given in which the load at the remote bus **2** is replaced by an induction motor with a rating of 280 kW (375 HP), 480 V. The motor is turned on at time $t$ = 0.1 s. The voltage waveform recorded at the nearby sensor is processed by a function in the PQ menu, which produces the rms profile shown in **4**. It is seen that the motor starting results in a sag to 85 % for about 2 seconds, before settling at a steady state of 98 % voltage. In the real world, such a long-duration voltage depression can cause electronic and computer-based equipment to fail.

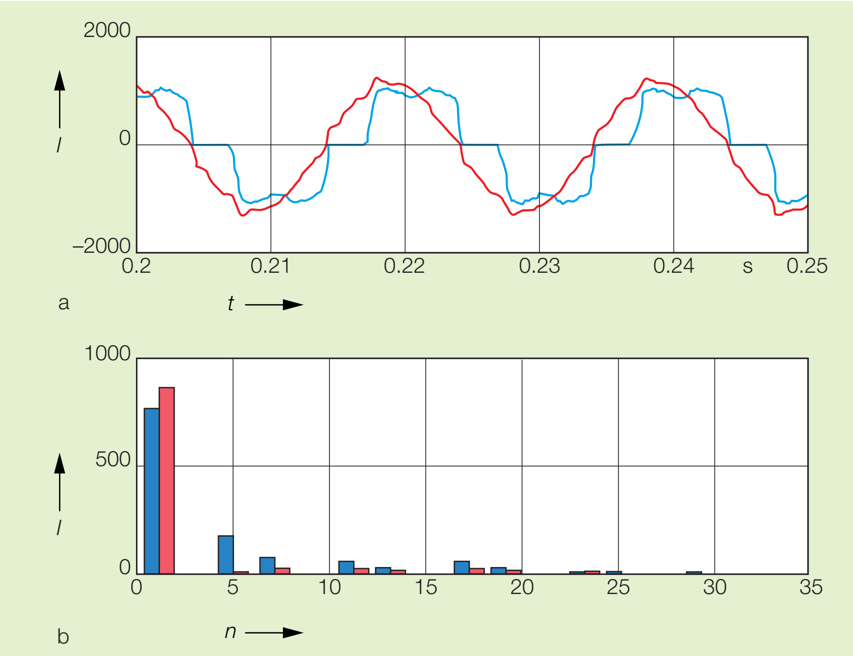
### Harmonics and filters

Power electronics devices, such as rectifiers, are known for injecting harmonic currents into the power network. This is a power quality problem, and can be mitigated by the use of harmonic filters. The example illustrates the use of a passive filter installed at the problem site to compensate for the generated harmonics. When the load at the remote bus (480 V) **2** is replaced by a rectifier (three-phase, full-wave diode bridge), the phase current at its terminal would be a 6-pulse current waveform – the blue curve in **5a**. With a 300-kVAr filter tuned to the 4.8th harmonic (or 240 Hz), the harmonic contents of the net current are reduced. The spectral analysis shown in **5b** reveals that the THD in the current is reduced from 26 % to around 5.5 %.

***Time-domain simulation of voltage sag due to a large motor starting*** **4**

*U* *Phase voltage (rms)*
*t* *Time*






***Analyzing the effectiveness of a harmonic filter tuned to the 4.8th harmonic*** **5**

a *Current before filter (blue) and after filter (red)*
b *Spectral analysis, showing total harmonic distortion in current reduced from 26.4% before filter (blue) to 5.5% after filter (red). The large reduction in THD is due to the fact that the amplitude of the fundamental component increases, whereas all harmonic components decrease.*
*I* *Current in amperes*
*n* *Harmonic orders*

## Concluding remarks

The design philosophy behind PQ-SMART was to re-use and combine off-the-shelf products already in existence and widely used within the company. This resulted in the choice of MATLAB, EMTP and the Windows-based PC platform.

As with any simulation software, simulated waveforms can only be realized through an elaborate library of components. Constructing a model for a new element is not a simple task, as it requires a thorough understanding of the actual physical device and the numerical methods, as well as many man-hours to validate the model. The choice of EMTP, as opposed to competing tools, was based on the fact that the EMTP engine is the most proven in the industry and, in particular, on the extensive library of components built in the past by the company's engineers. The shortcomings of EMTP are its input/output interface, but these are compensated for by MATLAB.

PQ-SMART became a fully functional package in 1996, after five man-months of development. The casual user does not have to learn MATLAB or EMTP in order to generate complex waveforms. PQ-SMART has a structure which allows the design team to add new equipment models as they become available.

In addition to power quality analysis and algorithm testing, the package has other important applications. System study engineers have access to a wide variety of system components, and are relieved of the laborious task of having to make and modify systems. Sales representatives can run the tool from a laptop computer to demonstrate to their customers the operation and benefit of an item of equipment.

## References

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## Authors' addresses

Khoi Vu
Le Tang
ABB Power T&D Company Inc
1021 Main Campus Drive
Raleigh, NC 27606
USA
Telefax: +1 919 856 2411
Email:
khoi.vu@ustra.mail.abb.com
le.tang@ustra.mail.abb.com

Kevin J. Timko
ABB Power T&d Company Inc
110 Corning Road
Cary, NC 39207
USA
Telefax: +1 919 233 5601
Email:
kevin.j.timko@ustra.mail.abb.com

Damir Novosel
ABB T&D Technology Ltd
CH-5405 Dättwil
Switzerland
Telefax: +41 56 486 7386
E-mail:
damir.novosel@chtet.mail.abb.com

Harri Kuisti
Tapio Hakola
ABB Transmit Oy
P.O. box
FIN-65101 Vaasa
Finland
Telefax: +358 1022 41599
Email:
harri.kuisti@fimit.mail.abb.com
tapio.hakola@fimit.mail.abb.com

# Intelligent substation automation – monitoring and diagnostics in HV switchgear installations

**Expanding on modern substation automation, in which all the bay-oriented functions are integrated in the bay cubicle, efforts are now being focused on moving the 'intelligence' even closer to the primary process. A precondition for this are new, 'smart' sensors and actuators for all the main measurements and setpoints, linked to each other and to the bay control level by a field bus. Such a concept allows cost-optimized, fully redundant acquisition and processing of all the operating variables, plus a diagnostics and monitoring system that covers the entire substation.**

Protection and process control systems are installed in power networks and substations to provide the technical platform for optimized operation and monitoring of all the primary equipment. The tasks cover a wide area, beginning with the instrument transformer or switchgear drive mechanism and ending with complex network control and load management. Collectively, the individual components of such systems are referred to as the secondary technology. However, this term has in the past normally included supervision, interlocking, measurement and control in the substation secondary technology but excluded all the protection equipment. Similarly, monitoring and diagnostic aspects of the primary apparatus have been virtually ignored in the design of the control and monitoring system.

It is common practice today to routinely inspect the individual items of equipment, although the intervals between inspection can differ greatly, depending on the manufacturer and the type of apparatus. For safety reasons, the inspections may even be carried out ahead of schedule. This is because often no clear information is available about the lifetime of the individual components and discrepancies sometimes exist between the manufacturers' figures and the basic lifetime assumptions (25 to 40 years) for the primary equipment in the substation. Continuous, automatic diagnostics are usually restricted to self-checking of the numerical control and protection equipment. Equipment users, however, have difficulty judging the depth of the testing, since neither the algorithms that are used nor the schematics are made available by the manufacturers.

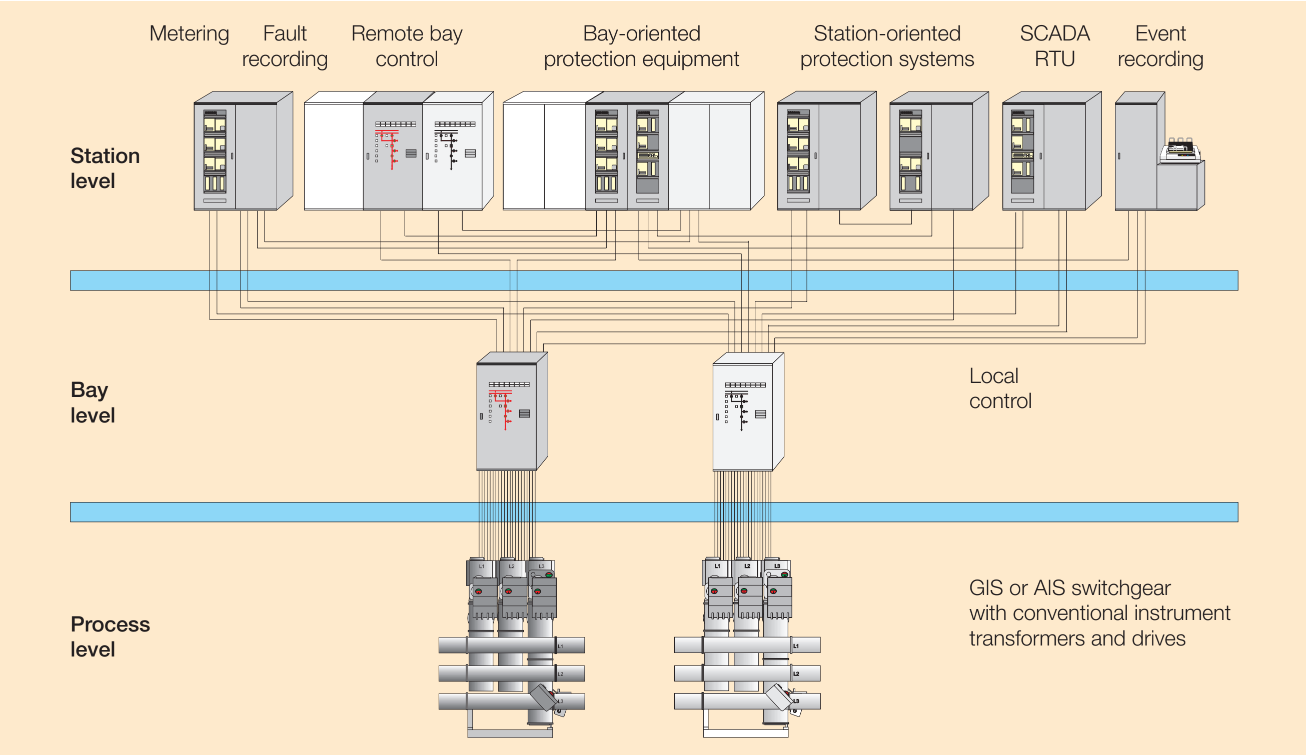
**Fred Engler**
**Alfred W. Jaussi**
ABB High Voltage Technologies Ltd

A monitoring system which is designed to cover the entire substation and which integrates continuous diagnostic checking of the primary equipment would allow regular inspections to be replaced by maintenance 'as required' and considerably shorten the mean time between a fault (which usually is not detected until the next inspection is carried out) and its clearance. Routine maintenance involves taking the high-voltage transformers, feeders and busbars out of service for preventive inspection, so its replacement by service 'as required' has a positive effect on the overall network control.

The concept of an intelligent switchbay allows for the first time optimum integration of the protection functions in the overall substation automation concept, while such switchbays also provide the basis for station-wide monitoring and diagnostics systems. Due to the size of these systems, only some of the more typical functions are given in the following.

Definitions of five terms used are given here for a better understanding of the subject matter:

- *Conventional control technology* (in fact, conventional control and protection technology): control technology based on electromechanical components, such as relays, contactors, switches, signal lamps, moving-coil elements. Some protection functions and station-wide system components are already electronics-based.
- *Modern control technology:* control technology based on numeric modules for protection and control functions at the bay level, computers at




***Conventional solution for substation control and protection*** **1**

the station level, and a serial (interbay) bus between the station level and the individual bays.

- *Intelligent control technology:* modern control technology, but extended such that individual functions at the bay level are moved closer to the primary equipment. The intelligent primary equipment and the bay level are linked via serial (process) buses, ie one bus per bay.
- *Smart GIS:* gas-insulated substation based on intelligent primary equipment.
- *PASS (Plug And Switch System):* gas-insulated switchbay of hybrid design; replaces AIS bays with a space-saving combination of circuit-breaker, disconnectors, earthing switch and current/voltage transformers, based on intelligent primary equipment.

The examples given in the following sections refer in the most part to gas-insulated switchgear, but could be applied just as easily to AIS systems or PASS.

### Hierarchies in the substation secondary technology

The different hierarchies in conventional and modern secondary technology within a substation have already been explained in [1]. Another source of valuable information is [2], which gives an especially detailed insight into the conventional designs and configurations for gas-insulated and air-insulated substations. The different hierarchies in modern secondary technology are given in [3], taking substations of different sizes as examples. The same source also looks at the new technologies for protection and control at the bay level.

**1** and **2** allow a comparison of the key elements of conventional and intelligent substation automation systems. The introduction of intelligent substation automation saves the space that is normally required for the protection and telecontrol equipment. Most of these functions are shifted towards the bay level and the station level. Since the large control panels are replaced by computerized workstations, the station control room can also be made smaller.

### Limits of conventional and modern control technology – advantages of intelligent substation automation

#### Wiring

[1] shows that one of the main objectives of introducing modern control technology is to reduce the amount of wiring between the different switchbays and between the bay level and station level. With conventional substation control there are between 200 and 500 signal links per bay, so that a typical 380-kV substation with two transformer and four line bays has up to 3,000 connections between the bay control cubicles and the protection/telecontrol area or control room alone.

A further 2,000 to 3,000 connections have to be reckoned with for the internal wiring in each switchbay, adding up to something like 20,000 signal connections for a six-bay substation. Intelligent substation control technology reduces these numbers by a factor of 30 to 60.

### Redundancy

In spite of – or perhaps precisely because of – the parallel wiring between the primary equipment and the local control panel and between the bay level and the protection/telecontrol room, there is no redundancy as such. Instead, to keep costs down individual 'users' (eg, systems for local control, line protection, remote control signalling, busbar protection, fault recording, revenue metering, etc) receive only those signals that they specifically require. Thus, no redundancy is provided for the individual sub-functions in conventional control technology. In its place there is partial redundancy of the overall function.

Intelligent substation automation allows, for the first time, a clearly scalable redundancy of all the secondary technology functions at all levels of the hierarchy within the substation. This is of special importance since, among other things, the rise in cost of the intelligent secondary technology is disproportionately smaller than the additional redundancy that it makes possible.

### Limits of conventional technology

The limits to functionality imposed by conventional control systems are a direct result of their technology. For every new secondary function additional equipment and wiring is needed, increasing both the volume and cost. The introduction of modern control systems represented a major technological advance as they clearly separated the hardware from the functions. The user therefore has, within certain limits, some influence on how the secondary technology functions are distributed between the different hardware units, especially at the bay level. For example, it is possible to mix the software functions of the local control computer and the main line protection and implement them simultaneously in two independent but identically structured hardware units. Redundancy at the bay level is therefore ensured.

The limits to this type of variable function allocation, however, exist there where different functions require access to similar process signals which are recorded separately. The current signal for the line protection and for monitoring, for example, can originate from different CT cores. Intelligent substation automation allows unlimited allocation of every individual function to one or more freely chosen hardware units at every level in the hierarchy.

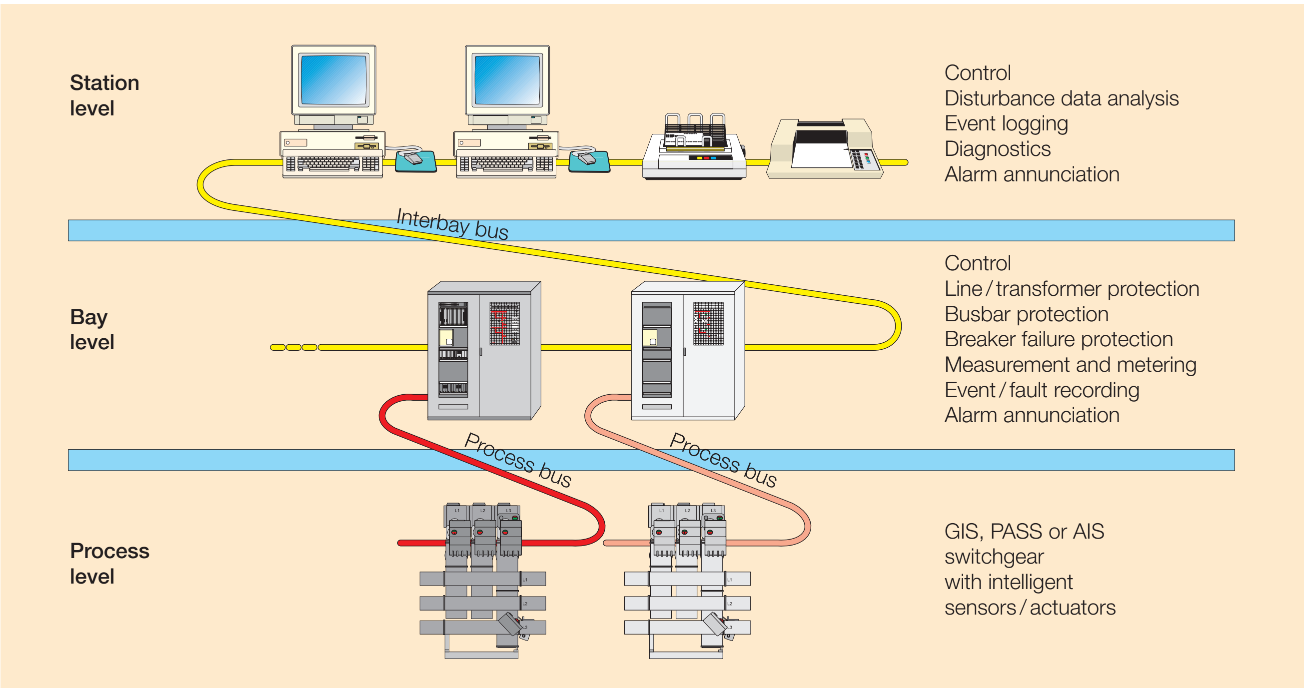
## Structure of an intelligent switchbay

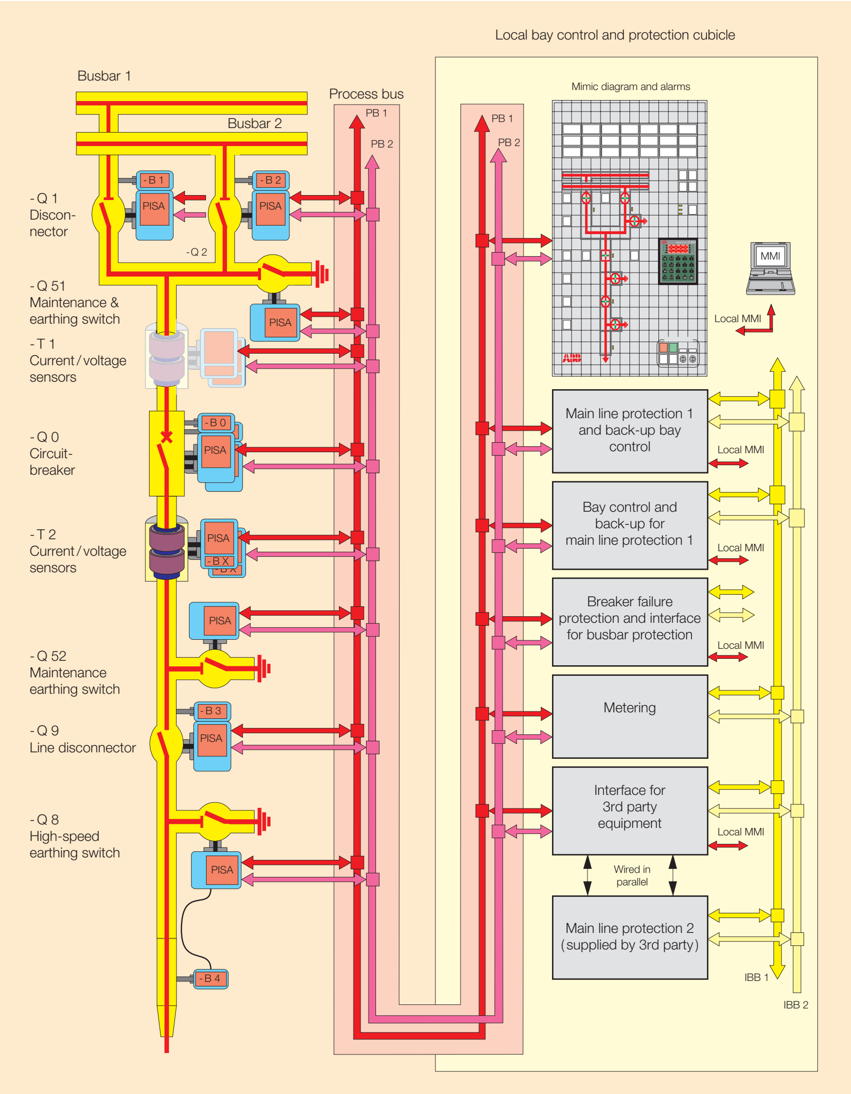
### Components at the process and bay level

The intelligent switchbay **3** comprises the following main hardware, software and communication components:

- Sensors and actuators for the conversion of physical changes in the substation into electrical signals (eg, measured values) or vice versa (eg,

***Intelligent solution for substation automation*** **2**






***Structure of the intelligent switchbay*** **3**

control signals). They form the link between the primary equipment in the switchbay and the secondary systems.

- PISAs (Process Interface for Sensors and Actuators). These form the level closest to the process (hereafter referred to as the process level) at which electronic signal processing takes place within the intelligent switchbay. PISAs and their respective sensors and actuators are designed as integral units and are mounted directly on or in the primary equipment.
- The bay level, with a specified number of universally designed electronic units housed in the local control panel. These units handle all the bay-oriented functions, such as power line protection, bay interlocking, bay control, synchrochecking and/or synchronization, bay-sharing of the busbar and circuit-breaker failure protection, intelligent switching, active and reactive power metering, event and disturbance recording, etc.
- Process bus (PB), connecting all the PISAs within a switchbay to each other and to the local control panel. The process bus is the communication medium for all information, such as measured values, trip signals, general control and diagnostic signals, etc, between the process and the bay levels.
- Interbay bus (IBB), interconnecting all the bays at the same voltage level and linking them to the station level.
- A comprehensive software package with all the system database, MMI and application modules required to activate the above components. This software package is installed in its entirety in the running installation.
- Another software package containing all the engineering, calibration, fault-finding and test modules required to define and activate the secondary system functions of the switchbay. This software is not available in its entirety when the systems are up and running.
- An easy-to-use programming and test system (PTS) for installing the above software packages and for the input and simulation of signals during configuration, testing and commissioning.

### Demands made on process and interbay bus communication

The process bus and interbay bus are designed to facilitate several modes of communication:

- Continuous, time-deterministic communication of fast-sampled analogue values (eg, current and voltage signals)
- Occasional, but time-deterministic transmission of binary telegrams (eg, interlocking data)
- Occasional, but fast transmission of binary values (eg, trip signals)
- Continuous but non-urgent communication of slow-sampled binary values (eg, monitoring and diagnostic data)
- Occasional, non-urgent, block-oriented communication (eg, disturbance report data or for downloading updated software)

To ensure that signals at the bay level are transmitted in the correct sequence, the process and interbay bus time-stamps all of the system signals. The master clock can be located anywhere in the communication system, but is normally integrated in the station-level computer.

**Monitoring and diagnostics in substations**

The sensors and actuators can be divided into five groups, according to their importance:

- Sensors for current and voltage measurement
- Actuators for circuit-breakers
- Sensors for gas density measurement
- Actuators for disconnectors and earthing switches
- Sensors for all other physical phenomena, such as arcing, partial discharge, temperatures, changes in lengths, etc

The continuous, uninterrupted functionality of the first three is vital for the operation of an installation. Because of this, at least the electronics of these sensors and actuators should be configured redundantly.

Detailed descriptions of several of the sensors used are given in [1] and [4].

## Examples of continuous monitoring functions

*Gas density monitoring and leakage diagnostics*

Whereas conventional gas density monitors measure only two or three predefined density levels to check for upward or downward deviation, an intelligent gas density sensor is able to measure continuously and precisely the instantaneous gas density. Leaks causing a heavy loss of gas can therefore be identified instantly. Continuous measuring of the gas density and non-stop signalling of the data to the bay and station levels has another advantage: the long-time behaviour of all the gas-tight compartments in a substation can be recorded and displayed. A trend analysis allows the diagnostic software to calculate the last date for refilling with gas, making it easier to schedule substation maintenance.

*Partial discharge monitoring and sparkover diagnostics*

Research and development laboratories have in recent years devoted a great deal of time and effort to the measurement of partial discharge in gas-insulated substations. Acoustic or electrostatic sensors are the current state of the art. At the customer's request these sensors are integrated in the substation, where they generate huge quantities of data at the bay and station levels. The demands this makes on the communication system depend on the local preprocessing capability, and can quickly grow to several times all the other communication needs of the substation added together. The difficulty here is drawing the right conclusions from the large amount of available recorded data, eg identifying the possible development of a high-voltage sparkover. This has to be predicted with sufficient accuracy to be able to draw up a schedule for taking that part of the substation involved out of service in order to carry out maintenance. Since the various installed systems tend to either under-function or over-function, depending on their parameterization, continuous partial discharge monitoring has not yet managed to generally establish itself. Such monitoring systems are often operated offline, ie the individual sensor signals are recorded at regular intervals and compared with earlier values.

*Arc monitoring and sparkover diagnostics*

Another type of sparkover diagnosis involves arc monitoring. Optical sensors continuously check the gas compartments for possible arcs and signal their occurrence to the bay and station levels. As with partial discharge monitoring, the traditional methods have the tendency to either under-function or over-function, so the sensor signals are not re-used direct, eg by the busbar protection system. The diagnostic software allows a kind of post-mortem diagnosis, with the gas compartment in which a sparkover has occurred being identified after the event. With this method it is at least possible to localize the part of the substation which has to be scheduled for maintenance.

The next step will be to refine preprocessing criteria or partial discharge and arc monitoring such that over-functioning and under-functioning are eliminated completely and the results of the monitoring can be integrated directly in the operation of the substation.

## Examples of a non-continuous monitoring function

*'Path-time' function of the circuit-breaker contacts*

**4** shows the block diagram of an intelligent circuit-breaker drive mechanism. Two position sensors measure the actual compression of the stored-energy disc spring and rod that operates the primary contacts. In the factory the assembled and tested circuit-breakers are operated several times with different loads and the path-time values measured by the position sensors are permanently and indelibly stored in the PISA. Every time the switch is operated in service the measured path-time values are compared, in each case linked to the load, with these as-built values stored in the product data memory. The actual status of the drive mechanism can be derived from the difference between the two values. Using this status as a basis, the diagnostics software at the station level can determine the date on which the next inspection should take place.

**Example of a direct diagnostics function**

*Quasi-continuous function diagnosis of the drive mechanisms of disconnectors and earthing switches*

It is common practice when operating substations to control the power network through operation of just the circuit-breakers, whenever possible keeping the disconnectors closed and the earthing switches open. As a result, the drive mechanisms of the disconnectors and earthing switches can suffer from months of non-use and become damaged. However, the same drive mechanisms are not allowed to under-function when fast changeover from one busbar to another becomes necessary. **5** shows the block diagram of an intelligent disconnect/earthing switch drive. The drive train consists of a controlled electric motor, a gearbox, a rotary transducer at the driving end and a position sensor at the output end. The gear reduction ratio is chosen such that even a small number of revolutions of the motor, although not resulting in any notable change in position of the primary contact, can be detected by the position sensor at the output end. This fact is utilized for diagnostic purposes, for example with the intelligent drive turning the shaft one revolution per week in the positive direction and in the week after in the negative direction of rotation. The values recorded by the two sensors are additionally linked to the measured motor currents to allow diagnosis of the drive and the primary-contact friction. If the drive is activated in the course of an actual switching operation, all the values measured over the full running time are recorded and compared with the indelibly stored product data. The diagnostics software at the station level uses the results to continuously calculate the date for the next inspection.

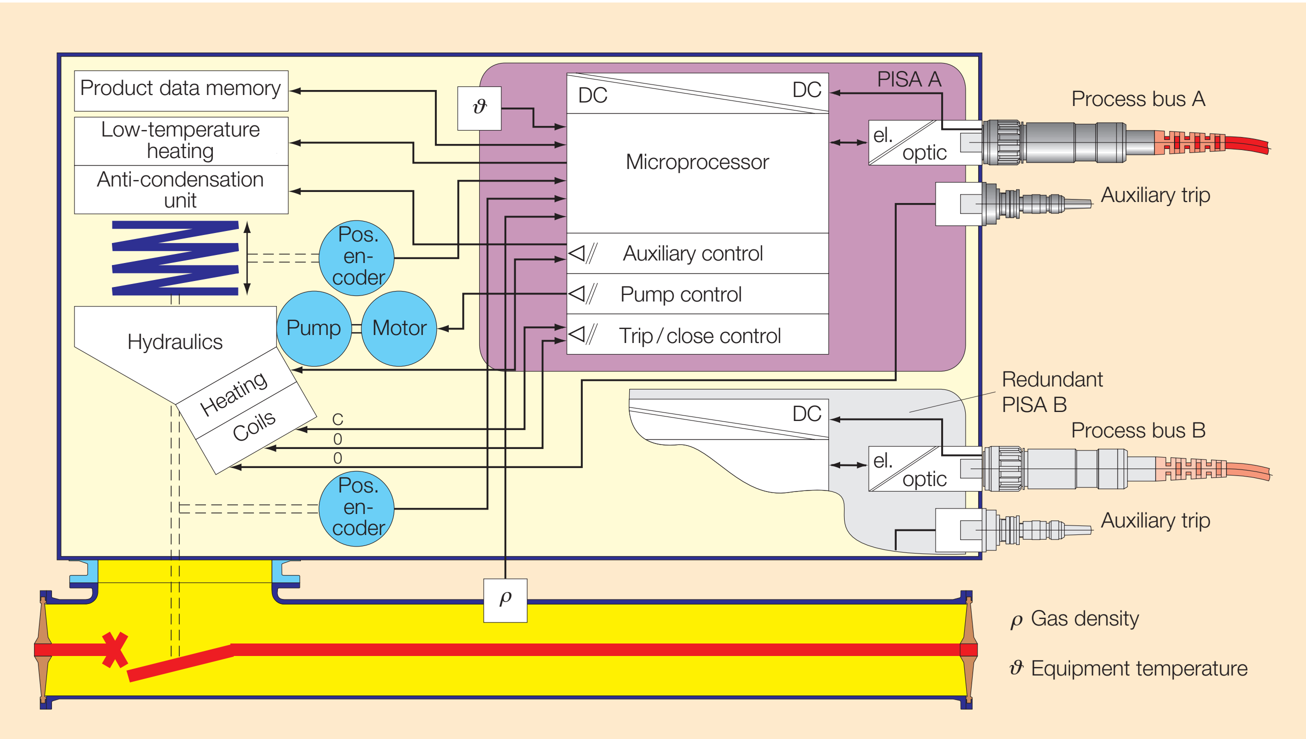
**Example of an indirect diagnostics function**

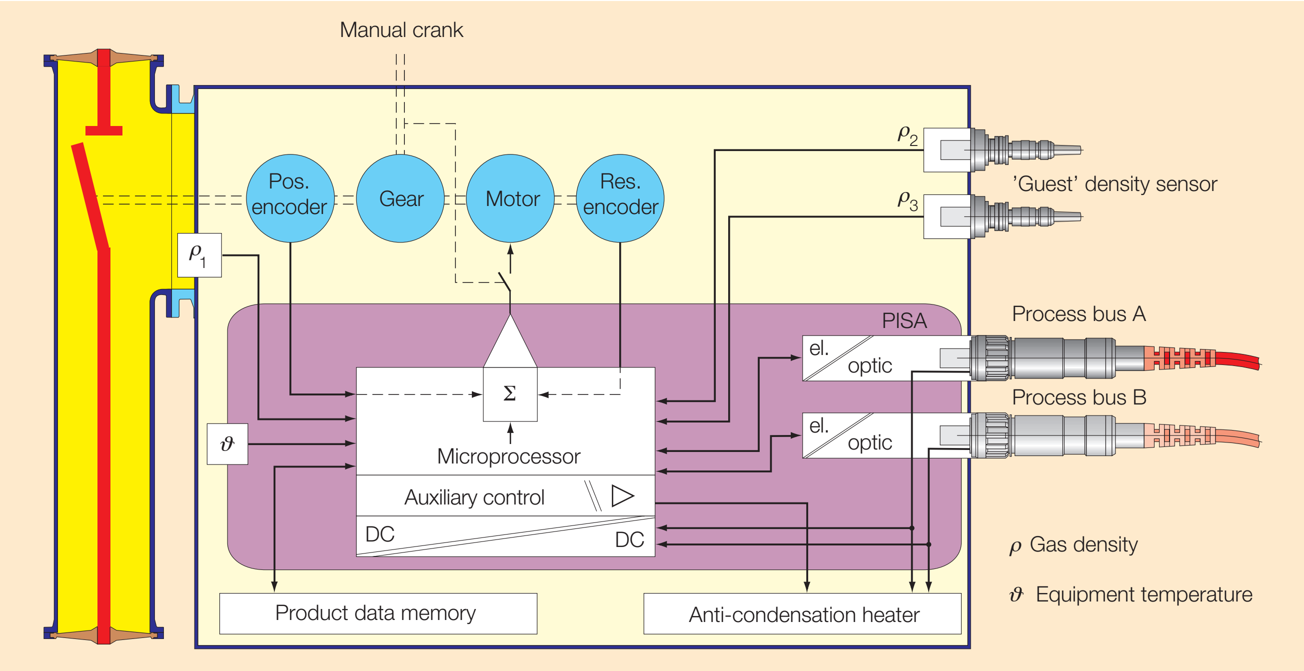
In the example involving the circuit-breaker, it is mentioned that the measured path-time values for the operating rod and disc-spring system can be linked to the actual load involved in switching. This is possible due to all the monitored values related to the drive mechanism as well as the sampled voltage and current values of the U/I sensor being time-stamped with an accuracy better than 25 microseconds. By comparing these instantaneous values with the originally stored characteristics it is possible to calculate the primary-contact erosion. The results of this diagnosis are a prerequisite for continuous updating of the parameter settings used to synchronize closing of the circuit-breaker.

**Demands made on monitoring sensors and retrofitting of existing primary equipment**

Before work began on the development of the primary hardware for the intelligent switchbay, ABB carried out countless laboratory tests on existing primary equipment to determine the sensitivity

***Block diagram of a circuit-breaker drive mechanism*** **4**






***Block diagram of a disconnect/earthing switch drive mechanism*** **5**

that would be required of the monitoring and diagnostics sensors and functions. These tests showed that:

- To obtain reproducible diagnostic values the primary equipment should be designed from the beginning with the monitoring requirements in mind.
- The diagnostics sensors have to be integrated in the direct chain of action of the primary equipment.
- To obtain useful values for comparison it is essential for the product data representing the original mechanical behaviour of all the primary equipment to be stored and retrievable over the entire lifetime of the apparatus.
- The sensors must be fully integrated in the diagnostics concept. A defective sensor must be clearly distinguishable from defective primary apparatus.
- Sensors for monitoring and diagnostics functions often have to be custom-designed; very little of the series-produced equipment is usable. The sensors have to satisfy the highest reliability and lifetime requirements.

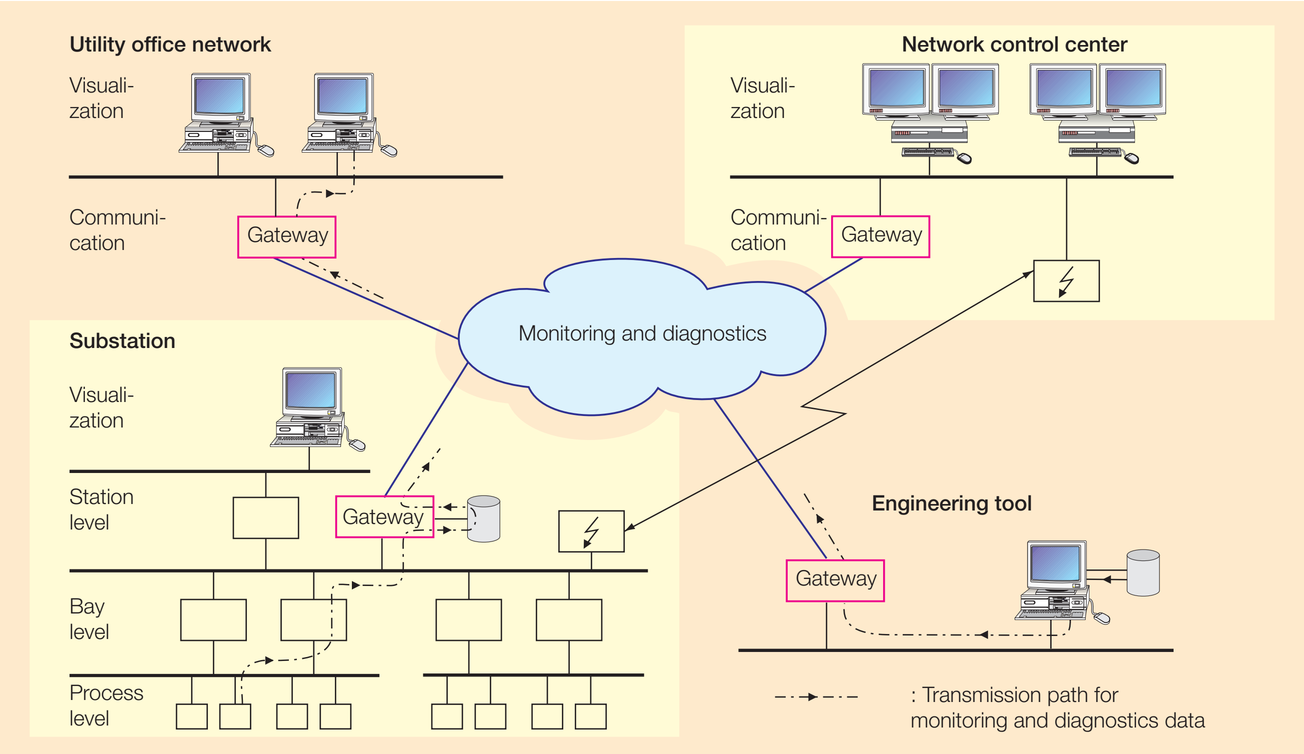
These requirements indicate that retrofitting existing primary equipment with diagnostic sensors is both difficult and cost-intensive. An additional problem is that in most cases the individual as-built mechanical values for the primary equipment are missing. For a retrofit project, the primary goal must be to plan and then implement a diagnostics concept tailored exactly to the substation in question. Substation operators having many years of experience with their switchgear and in possession of disturbance, inspection and maintenance reports, can provide valuable information, and may be able to draw up their own customized diagnostics concept. With a professionally designed and built diagnostics system in place, it is possible to predict more accurately the lifetime of existing substation components and/or increase the lifetime in order to shorten the pay-back time for the retrofit.

### Monitoring and diagnostics interconnections in the substation and network

In addition to the necessity of conditioning and, when necessary, storing the values collected in a substation it is equally imprtant to make these values available to a large number of users in a convenient and easily retrievable form.

**6** shows an overview of such a system. The values collected in the substation are transmitted to the monitoring and diagnostics network via a coupler, which conditions and stores them as necessary. The data can be accessed via the monitoring and diagnostics network, which also makes the configuration data used for substation planning and commissioning available for comparisons. Access to the network can be local, by means of switched modems, or direct, eg from the in-house network of a electric utility.

As shown in **6**, the monitoring and diagnostics network is clearly segregated from the command and control network. While this network can be




***Monitoring and diagnostics in interconnected substation and network configurations*** **6**

used to request information, it is not possible to use it for control purposes. The segregation ensures that operations management is kept apart in every respect from monitoring and maintenance. What is more, the two communication networks make completely different demands on reliability and availability.

### Benefits of intelligent substation automation

Intelligent substation automation permits new functions such as 'intelligent switching' at the bay level. Although these functions have nothing to do with the fundamental operation of the substation they allow, with the help of smart algorithms, both the space requirement and the cost of the primary components in the switchbay to be reduced.

The new components at the process level further allow, for the first time, uninterrupted monitoring of a wide range of signals. Thus, a continuous and comprehensive diagnosis of the primary equipment, including the sensors and actuators, is possible over its entire service life.

This local process diagnostics facility is complemented by powerful software packages at the bay and station levels which process the results of the station-wide monitoring and provide detailed diagnostic information based on a comparison with the product data and planning values. Maintenance work can therefore be scheduled to suit and carried out as it becomes necessary instead of routinely. This has benefits that include reduced overall lifetime costs for the substation.

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### Authors' address

Fred Engler
Alfred W. Jaussi
ABB High Voltage Technologies Ltd
P.O. box 8546
CH-8050 Zurich
Telefax: +41 1 318 3511
E-mail:
fred.engler@chhos.mail.abb.com

# Steam turbines retrofitted in record time

**Following a decision by the Finnish government in 1993 not to build another nuclear power plant, electric utility TVO looked into other ways of increasing production capacity to meet growing power demand. Modernizing power plants to improve the efficiency of existing components and achieve higher output is one of the most economical options open to utilities. ABB recently replaced the inner blocks of the low-pressure steam turbines in the 735-MW Olkiluoto 1 nuclear power plant in Finland after 17 years of trouble-free operation. As a result of the retrofit, the plant output was increased by almost 5 percent, or 36 MW. Close cooperation between the customer and supplier as well as between the different ABB companies involved enabled the project to be completed in record time.**

Almost 20 percent of the total electricity produced in Finland is generated in the two nuclear power plants Olkiluoto 1 and 2 **1** of Teollisuuden Voima Oy (TVO). Both of the units, which have been in operation for 17 years, are world-class performers with capacity factors as high as 94 percent. Base-load operation with only very short overhauls during fuel replacement characterize the operation of the two units.

**Feasibility studies**

Based on initial discussions with the customer in 1993, it was decided to carry out a preliminary study to identify the potential for improving the plant output. A modified heat balance with the current performance of the steam cycle, including all relevant changes to the major components and the current operating conditions, was established in close cooperation with the customer. In parallel with this, the consequences for the steam cycle of an increased reactor load were identified. The target for the preliminary study was to determine the limitations applying to the main components in terms of the:

- Maximum admissible load
- Potential for increasing efficiency
- Need for modernization
- Remaining lifetime

The study showed that the low-pressure (LP) turbines **2** offered the greatest potential for an improvement in steam cycle efficiency as well as the best cost-benefit ratio.

There are several reasons for the large potential for reducing losses in the existing low-pressure turbines by applying modern technology:

- The LP steam turbines installed in Olkiluoto were developed in the 1960s. At the time, only simplified methods of calculation were available with which to optimize the complex transonic flow in the last turbine stages. Today, design engineers use three-dimensional CFD (Computerized Fluid Dynamics) programs to understand and optimize the flow conditions in the turbine and the steam exhaust.
- Experience based on extensive measurements carried out on test turbines and full-scale machines has increased the understanding of loss mechanisms and has been used to calibrate numerical tools, such as CFD programs.
- Modern design and manufacturing tools, such as CAD (Computer Aided Design) and CAM (Computer Aided Manufacturing), combined with the latest milling machine technology, ensure economical and precise manufacturing of three-dimensional blades.

In addition, the study showed that it was economical to increase the reactor load to 115 percent. However, future operation at this load would require modifications to some of the components in the steam cycle.

As a result of the promising results of the preliminary study, the customer gave the go-ahead for the investigation to continue in order to obtain quantitative information on the efficiency improvement, the scope of supply, and the delivery and installation times.

Four major conditions had to be fulfilled by the turbine supplier:

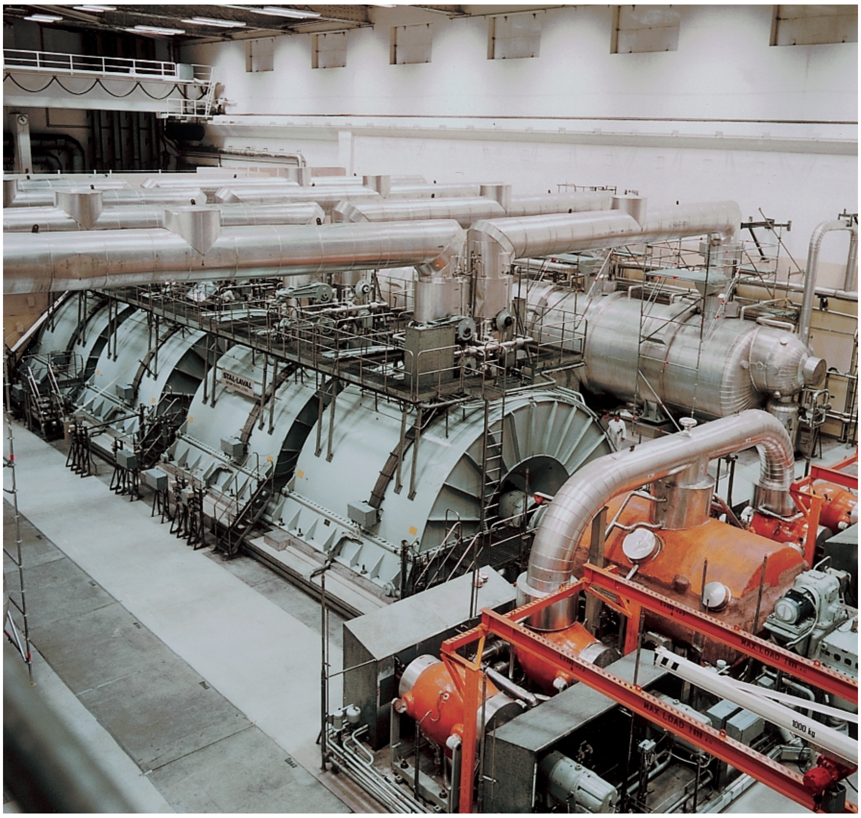
- Since the existing steam turbines did not suffer from any mechanical problems and could still be used even at increased reactor load, the increase in output due to the efficiency gain had to be large enough to justify the project economically.
- The proposed retrofit solution had to be based on proven technology to assure the customer that it would not have a negative impact on plant reliability.

**Bo Lindström**
**Carl-Henrik Ahrbom**
**Lars-Göran Karlsson**
ABB Stal

**Nils Lannefors**
ABB Power Generation

*Olkiluoto nuclear power plant (2×735 MW) in Finland* **1**

*Five-casing steam turbine in Olkiluoto 1. In the foreground is the high-pressure turbine, behind it the four low-pressure turbines.* **2**



- The installation of the new components would have to be completed during the very short planned outages, without any delays.
- Very high resistance to erosion-corrosion was required.

The preliminary study had shown that no standard LP steam turbine from the ABB product line was ideal for this retrofit application. It was therefore decided to carry out a feasibility study to look into the development of an optimum retrofit solution for Olkiluoto.

The decision was additionally supported by the fact that this LP turbine type is also ABB's most frequently sold LP turbine, with more than 100 rotors in service worldwide.

The feasibility study showed that to optimize the cost-benefit ratio for the LP steam turbine retrofit, only those parts which contribute to the efficiency improvement should be replaced. For the Olkiluoto project, the rotor, blading and blade carriers were selected for replacement. The inner casing had to be modified to fit the new blade carriers with an enlarged exhaust area **3**. As a result, the guides for the blade carriers had to be manufactured with a larger diameter, which led to the location of some of the carrier supports having to be changed. To speed up installation and save time during the short scheduled overhaul period, it was decided to manufacture new, modified inner casings for the Olkiluoto LP turbines.

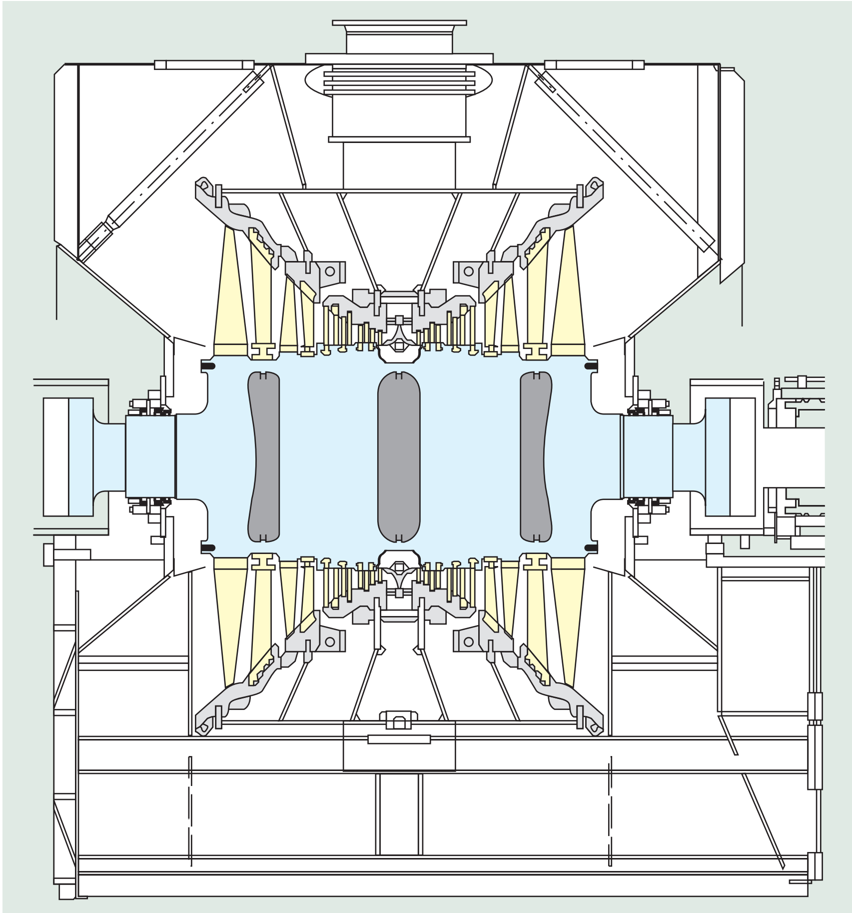
Based on the results of the study, the following LP turbine areas were identified as having the greatest potential for efficiency improvement:

- 3D high-performance reaction blading for the first four stages substantially improves the reaction stage efficiency compared with the former prismatic blading.
- An integral shroud on the next-to-last rotor blade results in lower tip leakage losses than with the former freestanding design with tip seal.
- A leaned last stator vane improves the working conditions for the last-stage blade and reduces losses due to vortices (secondary flow) at the endwalls **4**.
- Improved transonic profiles for the blades in the last two stages reduce losses caused by shock-induced flow separation.
- An enlarged exhaust area reduces the exhaust losses.
- An improved diffuser geometry increases the pressure recovery in the steam exhaust section **5**.

Together, these improvements result in a substantial gain in efficiency.

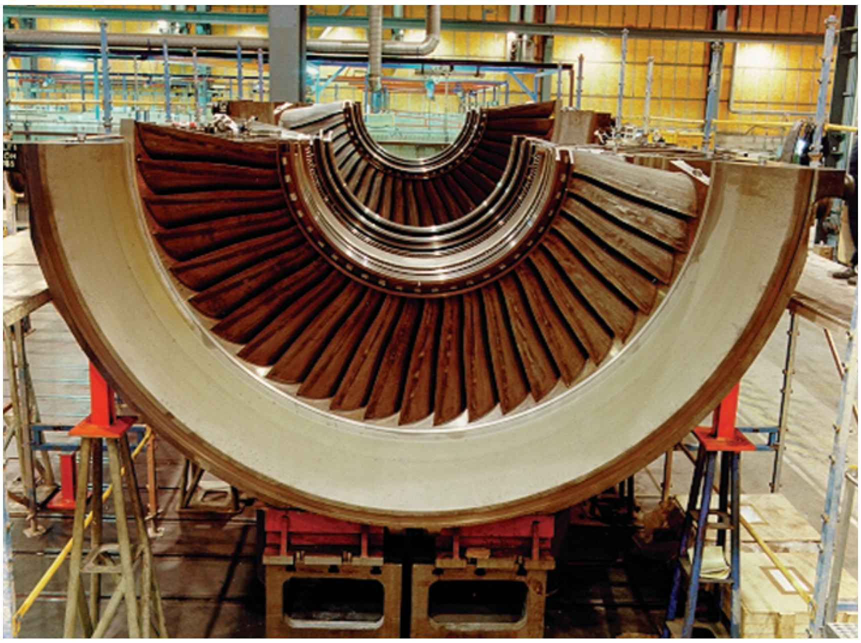
To reduce delivery time and development effort, it was decided to use existing technology for the rotating blades of the last two stages. The stationary blades for the last two stages were specially developed.

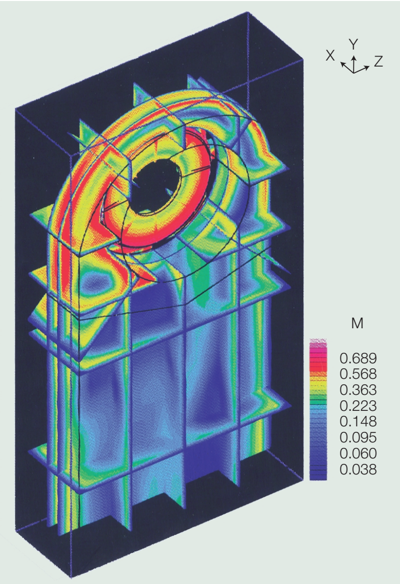
Since the customer required a solution with very high resistance to erosion-corrosion damage, four areas were defined for improved protection:



***Cross-section of the LP steam turbine retrofit solution for Olkiluoto. The new rotor and the new blading are coloured blue and yellow, the new blade carriers in the inner casing grey.*** **3**

***Leaned last-stage stator vanes assembled in the inner casing*** **4**






***Example of the calculated flow from the last-stage blade to the condenser neck in the LP steam turbine exhaust section*** **5**

M *Mach number (local steam velocity)*

- Steam chamber (inlet and bleed chambers)
- Steam channels
- Axial seals between the steam chambers
- Horizontal joint planes

To protect the steam chambers, the inside of the inner casings and the outside of the blade carriers were arc spray coated with 13 % chromium steel.

The steam channels were coated with a nickel-chromium alloy containing 80% chromium carbide using a high-velocity oxygen flame spray gun. Spraying was carried out by a robot to achieve homogeneous thickness and quality **6**. All spraying was performed in the ABB Stal workshop in Finspång.

The axial seals between the steam chambers were changed to radial-axial seals by inserting a piston ring of 13% chromium steel. All sealing surfaces in contact with the ring are also made of erosion-resistant material. The sealing strips of the horizontal joint consist of overlay welds with 18/8 stainless steel. The casings were also equipped with a new adjustable bottom guide to simplify alignment.

The engineering department of ABB Stal in Sweden and the steam turbine development department of ABB Power Generation in Switzerland cooperated closely in preparing the feasibility study, which subsequently formed the basis for the final tender. All customer requests could be met with the proposed solution. The contract was awarded to ABB just a few months after the feasibility study had been completed.

## Project execution

Based on the results of the 'load increase' feasibility study, the steam turbine of Olkiluoto 1 was adapted for operation at 107 % load during the 1996 overhaul. Olkiluoto 2 was adapted for 107 % load during 1997. Both units will be adapted for operation at 115 percent load during the overhaul in 1998.

| Project milestones | Date |
|---|---|
| 1. Initial discussions with customer. Modification of heat balances as basis for further studies | Apr 1993 |
| 2. Completion of preliminary study of possible efficiency improvements and reactor power increase | Sept 1993 |
| 3. Completion of feasibility study of LP retrofit solution | Feb 1994 |
| 4. Inquiry date | 2 Mar 1994 |
| 5. Tender date | 16 Apr 1994 |
| 6. Letter of intent from customer. Start of detailed development and design work | 10 Jun 1994 |
| 7. Signing of contract | 15 Aug 1994 |
| 8. Delivery of LP3 and LP4 for Olkiluoto 1 | 15 Apr 1996 |
| 9. Delivery of LP3 and LP4 for Olkiluoto 2 | 1 Apr 1997 |
| 10. Delivery of LP1 and LP2 for Olkiluoto 1 | 15 Apr 1997 |
| 11. Delivery of LP1 and LP2 for Olkiluoto 2 | 1 Apr 1998 |

## Site work

Planning of the site work started on June 10, 1994, the date of receipt of the letter of intent. The work on the turbine had to be coordinated with all the other activities on the turbine floor, including the generator retrofit, turbine control and safety system retrofit, and customer activities.

During the outage in 1996 the complete generator, which weighs 400 tonnes, was exchanged and the turbine control and safety system retrofitted. The high-pressure (HP) turbine was opened for the purpose of changing the swallowing capacity. The generator was replaced in 18 days, as stipulated by the contract. Retrofitting of the turbine control and safety system, adaptation of the HP steam turbine and retrofitting of the LP turbines 3 and 4 required only 16 days.

The LP turbine retrofits (turbines 1 and 2) were carried out during the scheduled outage in 1997 and took 14 days (in fact, 13 days and 19 hours) **7**, in accordance with the contract.

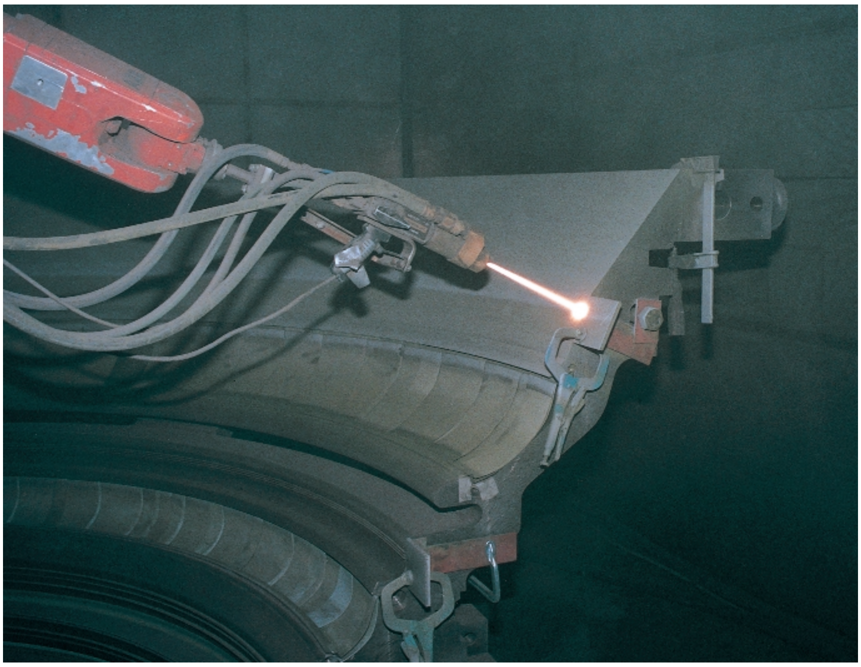
To ensure that all these activities could be carried out in such a short time, all the activities were planned in detail. A special crane time schedule was drawn up, showing the date and time, hour by hour, of all lifting activities **8**. The customer, ABB and subcontractors collaborated closely in the planning.

## Factors contributing to the success of the project

The speed with which the site work was successfully completed was due to a combination of know-how, experience in project management, and close cooperation with the customer. Contributing factors included well-trained, dedicated personnel, strong customer support and a permanent site supervisor, who coordinated the detailed planning on behalf of the client and ABB. A service planning, quality and administration tool called SIQS, for Service Integrated Quality System, assisted in this area.

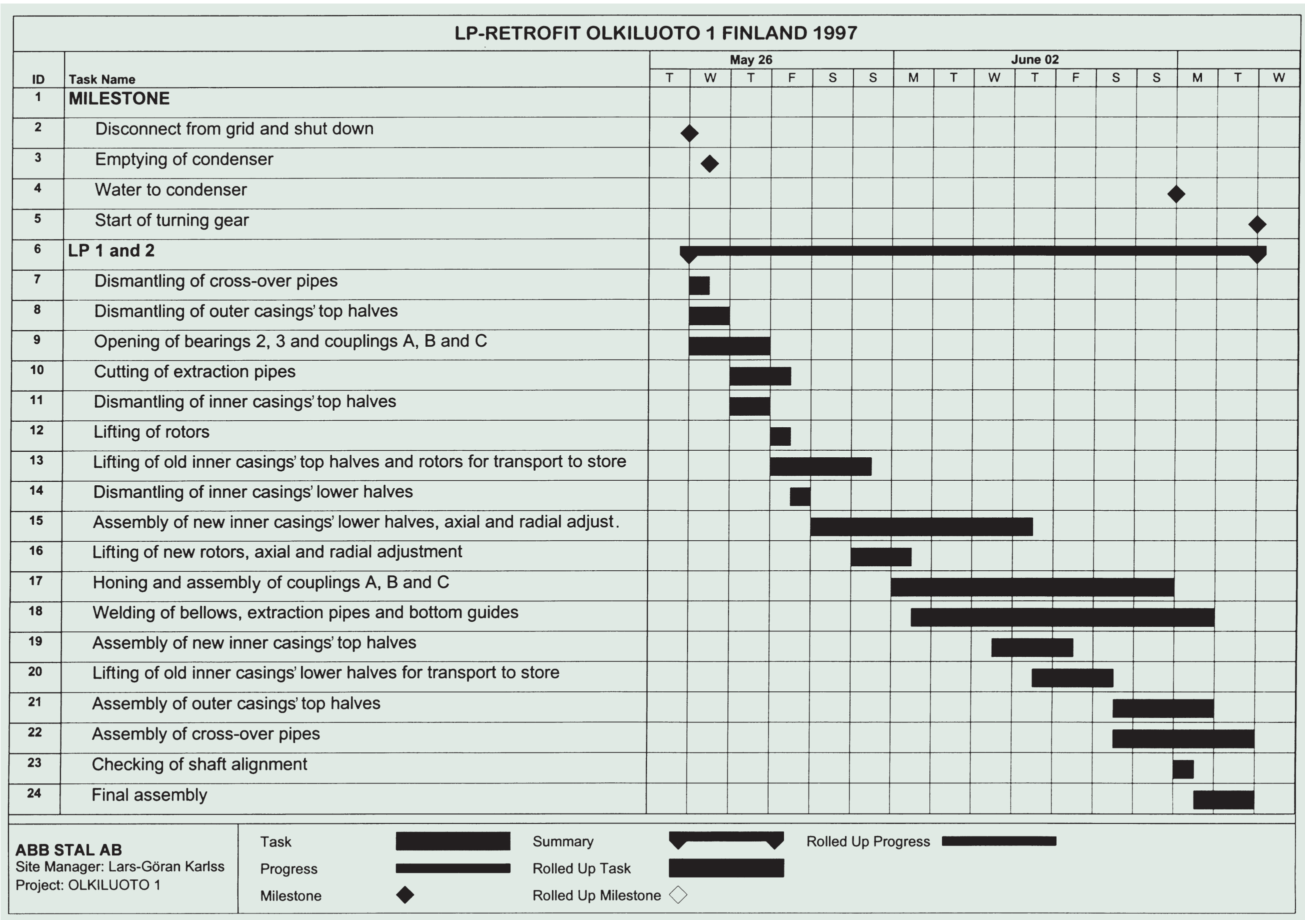
In all, there were 70 to 120 people from ABB Stal on the site. Engineers from the design department were in attendance during the entire outage period to make sure that there were no delays in contacting the home office. This meant that problems could be solved immediately, on the site. Work on the site went on 24 hours a day, 7 days a week.

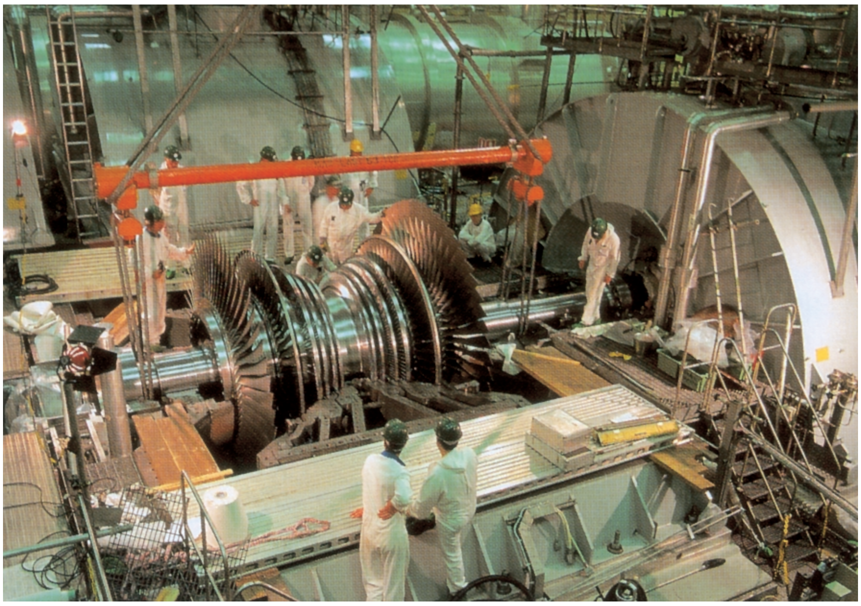
Also, meetings were held with subcontractors and the customer before the outage to discuss all activities, including the crane operations.



***Robot being used for high-velocity oxygen flame spraying of the blade carrier*** **6**

***Time schedule for the site work needed to install the new LP inner blocks during the Olkiluoto 1 overhaul in 1997*** **7**





***One of the new LP turbine rotors being lifted into position*** **8**

tional customer requirements, such as a short delivery time and very short on-site installation, have to be met. Steam turbines in many power plants do not suffer from mechanical problems, and for these units the increase in output possible by improving efficiency has to be sufficiently large to justify the project economically. Also, the continuing deregulation of the electricity market is making utilities look for a faster return on investment in retrofit projects.

All these aspects applied to the Olkiluoto project, which was successfully executed from project initiation to final performance measurements due to the close cooperation between the customer and supplier and between the different ABB companies involved.

## Performance measurements

Measurements were carried out during three test series to determine the performance of the old and new LP turbines at Olkiluoto 1. Between April 12 and 23, 1996, a baseline performance test was carried out prior to any changes being made. An intermediate performance test was then carried out between November 4 and 12, 1996, after LP turbines 3 and 4 had been replaced. Finally, a verification performance test was carried out between November 14 and December 5, 1997, after the replacement of the LP turbines 1 and 2.

The planning and execution of the tests focused on obtaining a low relative uncertainty between the three test series. To detect possible changes in the steam cycle and to evaluate the changed swallowing capacity of the HP turbine, a tracer measurement was made during the baseline and verification test series. This measurement also shows the absolute performance of the key components involved.

Some significant changes were made between the baseline test and the intermediate test:

- The swallowing capacity of the HP turbine was changed for the thermal load of 107 percent.
- The generator was replaced during the overhaul in 1996.
- The outer tubes in the condenser were replaced.
- Two drain coolers were replaced.

The tracer measurement was carried out by ABB Turbo Systems and the thermal measurement by ABB Stal. All the measurements were performed in close cooperation with the customer.

The results show an increase in output of 36 MW (ie, almost 5 %) at 100 % load due to the retrofitted LP turbines. The rise in output can be fully attributed to the improved efficiency of the modern LP steam turbine technology used, and exceeded the guarantee value.

## Concluding remarks

To be successful in the steam turbine retrofit business, it is essential to develop solutions in close cooperation with the customer rather than just present a product ‘off the shelf’. To be competitive today, it is not enough to just offer a package that increases efficiency and availability; additional customer requirements, such as a short delivery time and very short on-site installation, have to be met.


**Authors’ addresses**

Bo Lindström
Carl-Henrik Ahrbom
Lars-Göran Karlsson
ABB Stal AB
S-612 82 Finspång
Sweden
Telefax: +46 122 13357
E-mail:
bo.lindstrom@sesta.mail.abb.com
carl-henrik.ahrbom@sesta.mail.abb.com
lars-goran.karlsson@sesta.mail.abb.com

Nils Lannefors
ABB Power Generation Ltd
Dept. KWSD
CH-5401 Baden
Switzerland
Telefax: +41 56 205 31 79
E-mail:
nils.lannefors@chkra.mail.abb.com

# Economic generation of electric energy with modular reference power plants

**New power plant projects not only take many months to plan but also tie up much of the plant vendor's and customer's workforce for the duration of the planning. In addition, construction of the plant has to wait until pre-planning has ended. ABB Kraftwerke AG of Mannheim, Germany, has developed a modular reference steam power plant which can shorten the construction time, irrespective of the size of the plant and the site conditions, by at least 20 percent while also considerably reducing costs. The heart of the modular system is a three-dimensional CAD model, integrated in an Engineering Data Management system. Reference plants in four output classes have been pre-engineered in detail using this model. Alternative self-contained concepts are also available for clients requiring customized solutions. The total plant concept is ready almost immediately after signing of the contract, so that construction can start at once and contracts can be placed with local companies at the earliest possible dates. Power plants already under construction as well as several other projects confirm the benefits of the concept.**

A close look at the world's power plant markets, and especially at the concepts employed for coal-fired steam power plants, shows that the situation in the highly industrialized countries differs greatly from that in the developing countries.

In the industrialized countries plants operating with high-temperature processes, integrated coal gasification or coal-fired combined cycle power plants, in which steam turbines are supplied with heat from the exhaust gases of gas turbines, compete for the highest efficiencies, best fuel utilization and lowest pollutant emissions. At the other end of the scale, electricity is produced for the emerging economies by steam power plants based on proven technology for the simple conversion of energy. These 'workhorses' are mainly required to exhibit good availability, be rugged, have a long service life, tolerate poor-quality fuels and sometimes less than professional operation, and make only minimal demands on maintenance and repair.

**Dr. Ulrich Häuser**
**Peter Beyer**
**Dr. Joachim Engel**
ABB Kraftwerke AG

Power station vendors offering new plants in these markets must address two main issues:

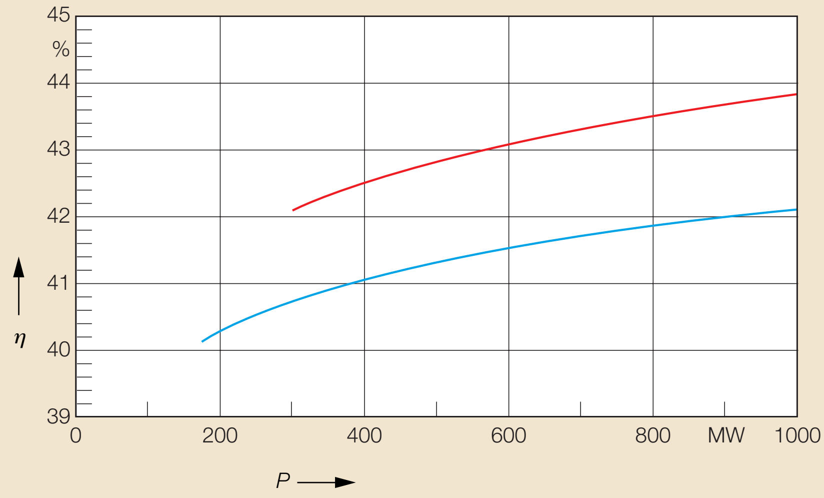
- They must work together with the customer in developing financing models that can be applied to the project.
- Plant design and project managment details have to be worked out that allow the energy demand to be met as quickly as possible.

In many emerging markets in Asia, Central and South America, an increase in power plant capacity is long overdue. As a rule the utilities in these countries also expect the supplier to assist in the financing of projects.

### Modular designs lower costs and save time

ABB has the technology capability necessary to successfully participate in the race for ever-higher efficiencies as well as compete internationally for orders in developing countries. With the latter markets in mind, ABB developed the modular 'reference power plant' (RPP), a range of power station designs combining proven technology with the fastest possible construction, low costs and high availability. What was required was a fossil-fired power station, preferably for fuelling with the widely available sub-bituminous coal. Designs for other types of coal and liquid fuels were developed in parallel and are also a part of the modular RPP platform [1, 2].

All physical elements of the power plant, eg systems, subsystems, components, rooms, structures, etc, are pre-engineered as modules and optimized as part of the overall system. Distinct interfaces are defined for the 'key buildings',




***Standard net efficiencies of modular reference steam power plants*** **1**

Red *Supercritical plants*
Blue *Subcritical plants*

η *Net efficiency*
P *Power output*

such as the boiler house, turbine building and switchgear building, as well as the ancillary systems. By offering fully engineered alternative concepts for those components that determine the scheduling, customized designs are possible that compromise none of the customer benefits of the modular RPP, such as short delivery times and fast commissioning.

Planning was based on the assumption that the power plant would be designed for a sub-tropical climate and be water-cooled, ie the plant would be sited on the coast or next to a river where it can be reached by sea-going vessels. Important benefits for the plant owners are the short construction time, the minimization of risk on account of initial planning having already been completed, the advantages that come from dealing with a single main contractor, lower costs and a shorter pay-back time. It also has to be emphasized that optimization of the process increases with every new plant and that the collaboration between ABB companies in different countries allows the financing of projects to be tailored exactly to suit the requirements.

## Interdisciplinary power plant engineering

All of the know-how resources of the ABB Group went into the planning of the RPP concept [3, 4, 5]. For the steam generators, for example, the technologies employed come from ABB Combustion Engineering in the USA; the clean-air systems come from German as well as other ABB companies; the I&C systems are based mainly on the experience and products of ABB Kraftwerksleittechnik GmbH in Germany. German-based ABB Kraftwerke AG itself can supply the turbine-generator set, including the feedheater, condenser and electrotechnical equipment. In other words ABB offers one-stop shopping for the complete turnkey power plant, the only exception being the civil works on the power station site.

The result of the interdisciplinary development programme, which lasted several years, is a series of steam power plants with unit ratings of 175, 300, 600 and 900 MW – power classes that cover the perceived market profile.

The 175-MW plants operate in the subcritical range with typical live-steam data of 140 bar and 540 °C (the 540 °C also applying to reheating). For the ratings of 300, 600 and 900 MW, RPP versions are available for both subcritical and supercritical data. The live-steam pressure in these cases is 166 to 250 bar, the live-steam temperature being 540 °C and the reheat temperature 540 to 560 °C. An overview of the plant efficiencies routinely achieved with the RPP is given in **1**. It was assumed that the feedwater pumps in the subcritical processes are driven by electric motors and those in the supercritical processes by steam turbines.

All RPP power plants are based on proven components designed as modules **2**. During the engineering of the process these optimized systems are joined together to form a unit. The resulting heat balance diagram provides the basis for the operating concept and the layout of the I&C equipment. Simu-

**Pre-planned technical documentation**

- Site plan
- Plant layout
- Plant description
- Process and start-up diagram
- Construction plans
- Bills of quantities
- Component data and specifications
- Heat balance diagrams
- Electrical single-line diagrams
- I&C concept
- Mass balance sheets
- Spare parts
- Commissioning concept
- Project scheduling

lations were used to calculate and select dynamic operating sequences that serve as a 'realistic' basis for the process technology, which is then adapted to each specific project.

**3D-CAD allows power plants to be 'viewed' before construction begins**

The very latest CAD software available on the market is employed for three-dimensional planning of the power station. The resulting data and a large amount of information from the process engineering and electrotechnical areas are managed within a database developed by ABB and known by the name SECAD, for Simultaneous Engineering by Concurrent Access to Data [6].

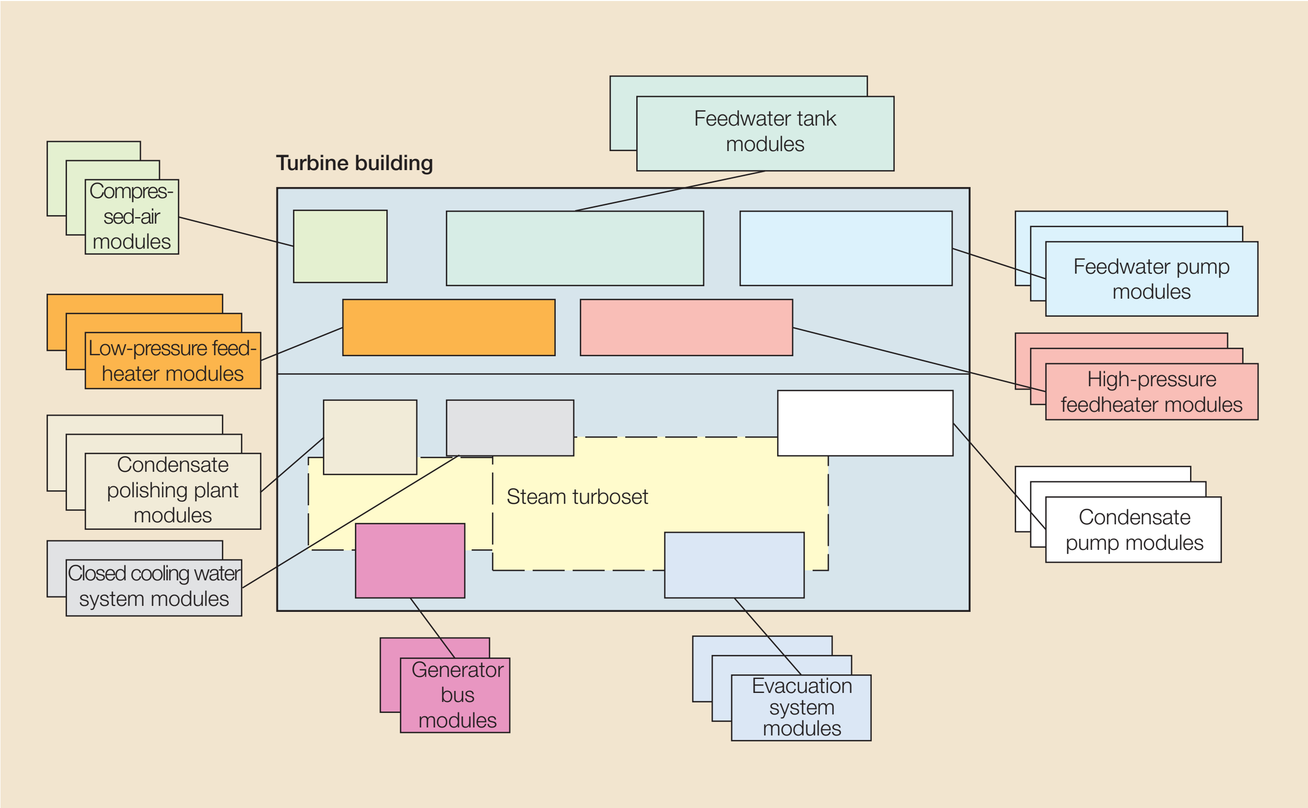
With the help of this software, the company has already engineered and built a large number of power plants all over the world. Field experience with the software is therefore an important asset of ABB. All the geometric data relating to the power plant are stored and linked to form a complete data model. By entering just a few commands, the user can 'walk through' the three-dimensional 'completed' power plant. Special software modules within the system continually check all the planning and engineering stages, for example for collision between ducting; free passage and unobstructed transportation routes are therefore ensured, while it is also checked that ducting with different dimensions or made of different materials is not joined together.

The system also ensures that changes are automatically taken into account in the data records of all the planning engineers linked via the company's internal data network and that the corresponding documents are modified accordingly. All the contracted project partners, even those in other countries, are therefore kept up to date about the present status of the planning. Due to the flexibility of the computer model it is also possible to 'retrofit' new technical developments or include special customer requirements in a very short time and at minimal cost.

The system not only generates all of the drawings (plan views, cross-sections or isometric projections) necessary for the civil works but also separate images of any desired single component. Complete manufacturing documents, with all dimensions and including the isometric drawings, can therefore be prepared. Close cooperation with the piping suppliers guarantees that planning specifications and quality standards are known and available already at the tendering stage.

This system capability and the possibility of having the basic engineering already completed and all the necessary plant diagrams available almost immedi-

***Reference steam power plant modules*** **2**



ately after signing of the contract, represent the largest saving in time in the execution of a project. Another advantage is the possibility of contracting the detailed engineering out to companies familiar with the local conditions; this is possible since, by working together with the future operator, it is possible to adapt the computer model to the particular project conditions already during the initial negotiations.

Providing the customer's infrastructure meets certain requirements and the site parameters are appropriate, work on the construction site can begin just six weeks after signing of the contract.

Detailed drawings, for example for subcontractors manufacturing component parts, can be prepared very quickly. The exact planning documents serve in such cases as a reliable starting point for production and make it easier to check that quality specifications are complied with. ABB views it as a special advantage to be able to increase the local scope of supply in order to boost the value added by the home country and at the same time reduce the financing needed for the power plant project.

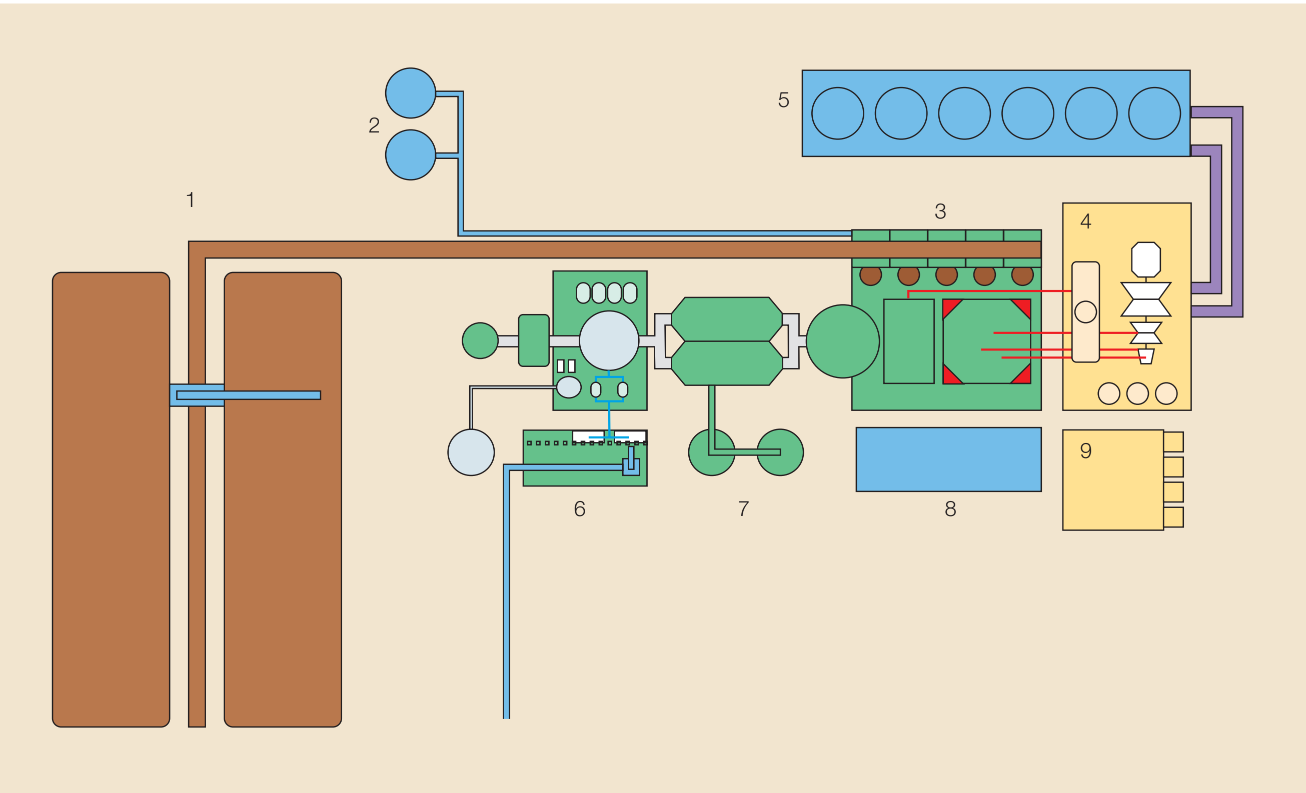
**Pre-engineered flexibility**

Every electric utility has its own strategy or in-house practices, eg for the feedwater supply, heat-exchangers or layout of the power plant buildings. The ABB modular RPP concept has great flexibility in this respect. The only buildings to have their positions fixed in relation to each other are the boiler, turbine and switchgear buildings **3**. Their interfaces are clearly defined and planned in such a way that construction can begin both simultaneously and independently. Since these 'key buildings' are critical to the scheduling, this independence plays an important role; in conventional power plant construction delays in the progress of one building often lead to overrunning of the schedules for the others. All the RPP ancillaries, such as the fuel supply system, administration building, water treatment plant, etc, can be freely arranged and adapted to suit the circumstances.

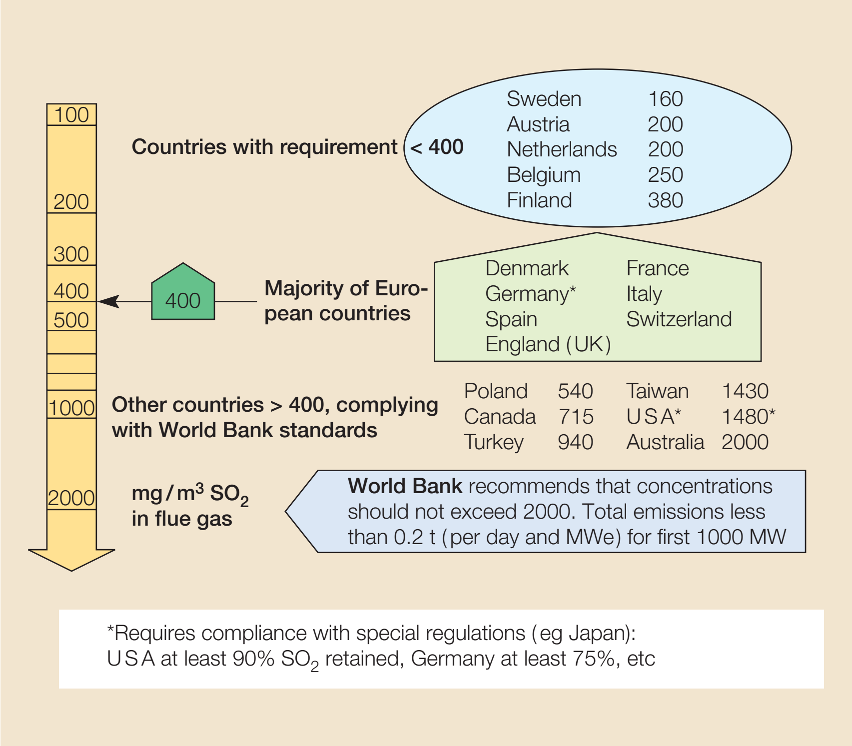
The client can also choose the feedwater pump drives (steam turbine or electric motor drives), plus the required redundancy. Alternative modules are included in the RPP concept so that the user can run through the different possibilities open to him on the screen. To replace two motor-driven pumps rated at 50 % each by a turbine-driven pump with

***Reference steam power plant: layout with the main buildings*** **3**

1 *Coal handling system*
2 *Start-up fuel*
3 *Steam generator*
4 *Turbine building*
5 *Cooling tower*
6 *Flue gas desulfurization system*
7 *Electrostatic precipitator*
8 *Auxiliary building*
9 *Switchgear building*



100 % rating or three 50 % feedwater pumps with electric motor drives, for example, all the user has to do is press some buttons. The same versatility applies to the heat-exchangers: the user can choose between plate- or tube-type heat-exchangers, complete with all the required pipe connections, foundations and support structures. Condensers are available in single-flow or double-flow design, and the high-pressure feed-heaters can be positioned upright or horizontally.




***Outline of permissible $SO_2$ emission limits in various countries, neglecting further requirements which are decisive for the plant design, such as half-hour values, annual averages, etc*** **4**

### Broad range of steam generators for project-specific steam data

The wide choice of components is also the basis for deciding whether the operation of the power plant should be subcritical or supercritical. A supercritical process is also possible with the 300-MW units offered by the RPP platform. The superiority of this technology is proven in the Western world and in parts of Asia. What is now necessary is to make this more efficient process, which also has less impact on the environment, familiar and acceptable to the emerging economies. This will not be without problems, since the capital investment for a supercritical power plant is slightly higher than for a conventional plant and is amortized only in the medium term, depending on fuel costs and other assessment criteria. In the industrial countries, at least, the supercritical plants are increasing their market share considerably. It remains to be seen which strategy the potential operators of plants in the emerging markets will follow.

A broad spectrum of boilers can be used with the modular RPP: ABB Combustion Engineering in the USA builds natural draft boilers for turbosets with low steam data, boilers with controlled circulation for higher but still subcritical steam pressures, and a series of forced-flow boilers for supercritical steam parameters.

The boilers with controlled circulation were developed in order to:

- Secure reliable heat transfer in the subcritical range under all operating conditions.
- Be capable of responding to fast load changes as dictated by the electrical grid.

The combination of supercritical steam data and modern turbine technology ensures higher efficiencies, a lower specific fuel consumption and therefore more profitable power generation, without compromising high reliability, availability and a maintenance-friendly design. Boilers are available which have been developed for combined sliding and fixed pressure operation, for both base-load and medium-load operation. ABB has experience with vertical and spiral-wound furnace wall tube arrangements.

### Flue-gas cleaning for improved environmental compatibility

While in Europe it is standard procedure to pass the cooled exhaust gases leaving the boiler through a flue-gas cleaning system to remove harmful pollutants, this technology still represents new territory for many of the world's countries. In some regions, financing by the World Bank can depend on power plants meeting at least the minimum requirements for environmentally compatible operation, as indicated for example in **4**, which gives $SO_2$ emission limits for various countries.

It goes without saying that the modular RPP platform includes pre-engineered systems for the removal of particulates, sulfur and $NO_x$ from the flue gases, supplemented by modules for environmentally sound water and waste management. The latter take into account the experience and know-how of

European power plant vendors and may help some potential power plant operators to navigate the obstacles in this field. The modules have been designed such that even completed projects can be upgraded at any time to comply with new, more ambitious national environmental standards 5 [8].

**Highly developed ABB turbine technology**

Steam turbines for sliding or fixed pressure operation in a subcritical or supercritical process have long represented a valuable share of the ABB reference plants. The possible combination of low-pressure turbine modules with the widest range of condenser designs and arrangements facilitates operating modes aimed at optimum economy even with extreme cooling-water temperatures.

It is important here to mention here that even for the highest RPP ratings ABB can install an impulse wheel in the high-pressure steam turbine to provide the basis for a control stage. Fitting such a wheel allows simple reserves to be provided in less-stable networks without adversely affecting the efficiency.

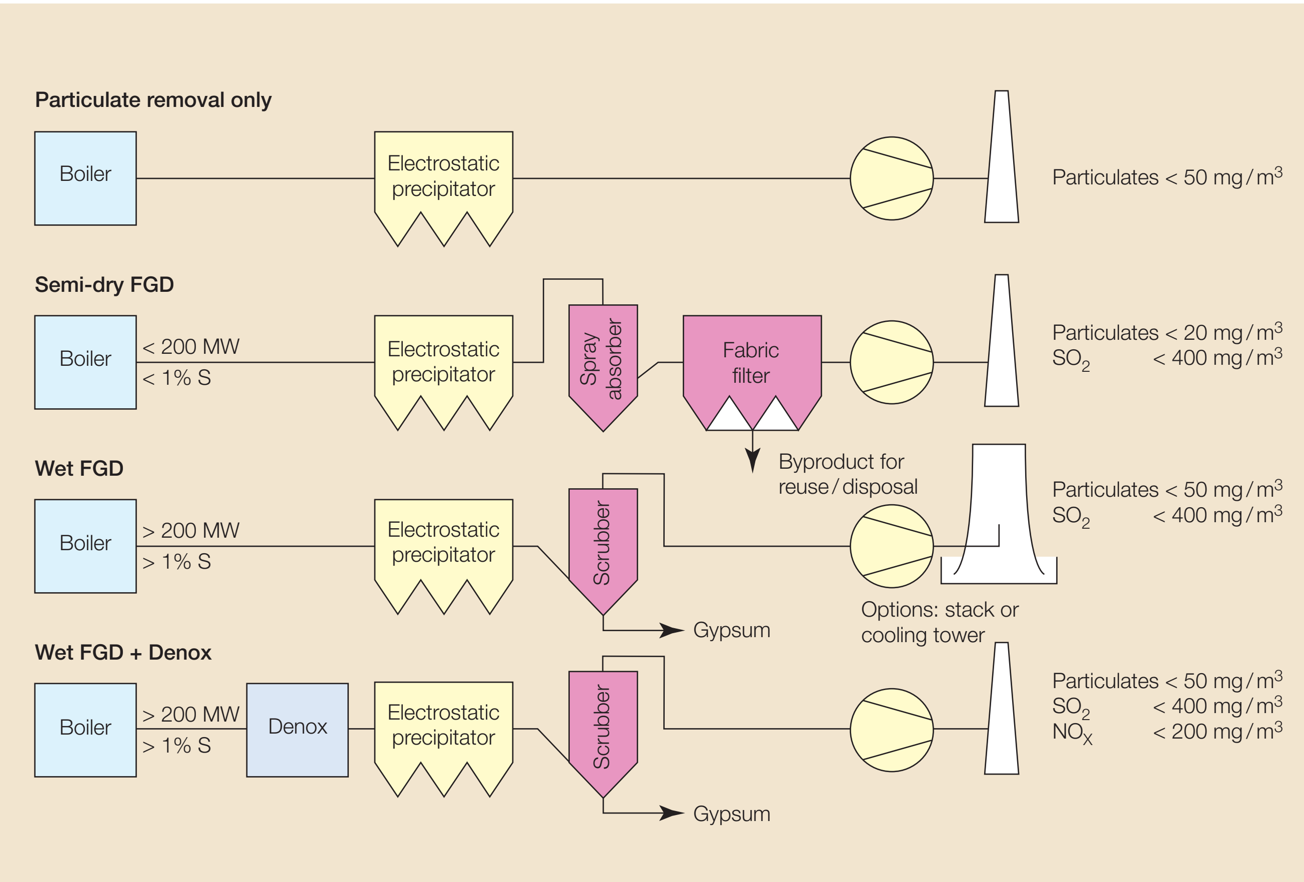
**Focus on financing**

The importance of financing in the international power plant business today is underscored by a look at the orders for which ABB has been able to arrange financing in recent years: from a volume of approximately US$ 500 million in 1990, financing has risen to about ten times this figure. The market trend is therefore clear: against the background of deregulation and strong competition, the ability to arrange financing for power plant projects is increasingly becoming a decisive factor in winning orders. The same is true of the necessity to purchase power plant components and systems from different countries.

It is here that the advantages of the pre-engineered modular RPP comes to the fore: matching power plant parts can be manufactured at different locations all over the world.

Besides global sourcing, sophisticated multinational models for financing and securing loans, which also increase the value added by the country ordering the power plant, increasingly help to safeguard funding of the project. Here, ABB has the advantage of having companies located all over the globe. These companies are often the key to being able to successfully take advantage of international programmes for securing

*Flue-gas cleaning modules for a reference steam power plant* 5



loans. Financial engineering is therefore becoming increasingly important in the realization of planned projects in the emerging markets **6**.

ABB has founded two independent companies to handle in a professional way the complex financing and contractual issues involved:

- ABB Project & Trade Finance (PTF) arranges the supplying companies' export credit, funding, bank loans and financing by the World Bank and/or multinational development banks, and also arranges counter-trade deals, leasing and other similar financing models.
- ABB Energy Ventures has worldwide responsibility for the formation and management of Independent Power Producers (IPPs). ABB Energy Ventures has drawn up feasibility studies for 23 power plants of all types with ratings of more than 5,500 MW, led the contract negotiations and arranged the financing. At the present time, ABB has an IPP project on every continent.

As diverse as power plant technology presents itself – ranging from custom-built, 'one-off', top-end facilities for demanding high-tech operators to combinations of modules adapted to specific requirements – as diverse also are the possibilities for their realization. Experience with many different models for financing and operation make it possible for efficient power plants, adapted to suit, to be built quickly and cost-effectively. Once on stream they supply the electricity so urgently needed in the emerging economies, energy without which neither economic, technical nor social development is possible.

| between **Contracts** for | Country/ utility | Project developer | Operator | Power plant vendor | Banks | Fuel supplier |
|---|---|---|---|---|---|---|
| Power supply | ● | ● | ◐ | ◐ | ░ | |
| Power plant delivery (EPC) | | ● | ◐ | ● | ◐ | |
| Operation and maintenance | | ● | ● | ◐ | ░ | |
| Fuel supply | ◐ | ● | ◐ | ░ | ░ | ● |
| Loans | ◐ | ● | | ░ | ● | |
| Land purchase | ● | ● | | ░ | ░ | |

***BOO/BOT (Build, Own, Operate/Build, Own, Transfer) – contract structures for power plant projects*** **6**

● *Parties to contract*
◐ *Parties contributing to contract terms*
░ *Spheres of interest*

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## Authors' address


Dr. Ulrich Häuser
Peter Beyer
Dr. Joachim Engel
ABB Kraftwerke AG
P.O. box 100 351
D-68128 Mannheim
Germany
Telefax: +49 621 381 2642
E-mail:
ulrich.haeuser@dekwe.mail.abb.com.

# Environmentally friendly hybrid vehicles in commercial service

**Hybrid drive lines – a combination of electric motor and internal combustion engine – mitigate the environmental impact of road traffic by reducing vehicle emissions. ABB has unique experience in this area and is working together with Volvo to evaluate the technology during a three-year trial with two hybrid trucks in normal commercial service in Gothenburg, Sweden. Simulations have shown that fuel consumption is reduced and emissions considerably lower with the hybrid truck. In addition, hybrid trucks can be run with zero emissions in environmentally sensitive areas.**

ABB began research into small high-speed power plants and their possible use in hybrid drive systems at the end of the 1980s. Such drive systems could help to lower $CO_2$ emissions, which come mainly from road vehicles and are a major contributor to the greenhouse effect. The hybrid drive line – a combination of electric motor and internal combustion (IC) engine – is designed primarily to reduce emissions, but also allows vehicles to run entirely without emissions in particularly sensitive areas. This will enable it to comply with the zero-emissions standards that are likely to be introduced in certain urban areas in the foreseeable future.

Hybrid vehicles are intended primarily for transportation in areas which are particularly sensitive to exhaust gases or engine noise. All drivers of hybrid vehicles have to do when passing through such areas is switch to the electric mode in order to lower the noise level and stop emitting pollutants.

The first practical application of the hybrid drive line was demonstrated in 1992, when ABB and Volvo jointly developed a specially built vehicle called the Environmental Concept Car, or ECC [1]. This was equipped with a gas turbine and a directly driven high-speed generator. The same concept was also used later as the basis for two other projects: a truck used in distribution service, and a bus [2].

The third hybrid vehicle concept has now been introduced and is currently being demonstrated 1 by the haulage company TGM AB in the city of Gothenburg, Sweden. During a trial period that will last three years, the company will operate two trucks in regular distribution service, transporting goods every day in the city center and suburbs. The trial period has already begun and fuel consumption, emission and noise level data are being recorded. Other factors which are being studied and evaluated include driver acceptance of the new technology, road handling and vehicle response in everyday traffic situations (eg, acceleration capability in electric mode), service needs and other practical details.

**Niclas P. Berg**
ABB Hybrid Systems

## New concept has a range of objectives

The advantage of hybrid vehicles is that, by switching to the electric mode 2, drivers can run them in sensitive areas without emissions, the traction power being supplied by just the batteries. The vehicles are designed to simplify driving; no special skills are required. A brief, introductory training session should be sufficient to ensure that the vehicle's capabilities are efficiently utilized.

In the concept chosen for the two trucks, a diesel engine drives two permanent magnet generators, with the wheels driven by two induction motors via reduction gearing, a propeller shaft and a differential. ABB supplied the complete electrical drive line, including the equipment for monitoring and control.

## Hybrid vehicles used during the three-year trial

The hybrid vehicle is built around a standard Volvo FL6 truck, the electrical equipment being mainly located along its sides 3. The extra weight of the hybrid truck, compared with a conventional vehicle, is approximately three tonnes. Since the trucks will operate for several years in commercial traffic, components and technologies of proven durability and reliability are used as far as possible.

For the development and evaluation of hybrid vehicles, it is important to be able to collect component data which is based on service under everyday, real-world conditions. This information will be provided by the three-year trial now under way. The project stipulates that each vehicle is to travel an average distance of about 150 km per day, which is equivalent to a typical city distribution cycle. Of this distance, a total of 30 km can be run entirely in electric mode. *Table 1* shows the main vehicle data.

**Drive line**

The Volvo FL6 Hybrid is a series hybrid vehicle with the drive line shown in **4**. An auxiliary power unit (APU), consisting of diesel engine and two permanent magnet generators with rectifiers, provides power to an intermediate DC bus. The two strings of batteries are connected to the DC bus via two DC/DC converters. Nickel-cadmium (NiCd) batteries are used. They also supply power to the auxiliary power system, which includes chargers for the 12-V and 24-V batteries and a DC motor that drives a brake compressor and the steering servopump. The truck is driven by two induction motors.

The two sources of energy (ie, the diesel engine and batteries) can be combined in different ways. Operation of the drive line can be either in electric or hybrid mode. In electric mode all the power is provided by the batteries, in which case the vehicle range and performance are limited by the capacity of the batteries. The batteries are recharged during braking, when the electric motors act as generators. In hybrid mode, the mean power demand is met by the APU and the unit's surplus power is used to charge the batteries. During periods of high power consumption (eg, during acceleration) the batteries provide additional power to the electric motors. Control of the diesel engine is based on the total power needs of the vehicle. *Table 2* gives the drive line specification for the Volvo FL6 Hybrid.


***One of the two trucks fitted with a hybrid drive and now taking part in a three-year trial in central Gothenburg, Sweden, where it is being used to distribute goods*** **1**

**Table 1:**
**Main vehicle data**

| | |
|---|---|
| Top speed | 90 km/h |
| Range in electric mode | 15–30 km |
| Total weight, chassis | 8,300 kg |
| Additional weight for hybrid vehicle | 3,400 kg |
| Payload | 4,600 kg |
| Gradeability (at full load) | 16% |
| Vehicle length | 8.6 m |
| Vehicle height | 3.3 m |


***Controls in the truck cabin*** **2**

The truck's vehicle management unit (VMU) is mainly responsible for controlling the drive line, which it does by influencing the subsystems in response to the commands from the driver. An instrument computer unit (ICU) controls the dashboard instruments in the cabin, and also interfaces with the diesel engine control unit. The battery management unit (BMU) monitors the condition of the batteries and also communicates with the VMU.

The diesel engine is located in the same position as in a standard truck. All the additonal units are placed behind the driver's cab, underneath the cargo body **3**.

The electric motors and generators are mounted in a subframe in the mid-section of the truck. The inverters are located on the right-hand side of the vehicle, and the two battery units are mounted on each side. The power electronics equipment for the auxiliary power system, the DC/DC converters, the VMU and other electrical apparatus are installed in a special box behind the rear axle.

### Control

When the truck is driven in electric mode, all the power is taken from the batteries. The DC/DC converters keep the DC bus voltage constant at 600 V. In hybrid mode, the motor power is supplied by the APU and, when required, from the batteries. The power flow follows the formula:

$$P_{eds} = P_{gen} + \eta_{dcdc} (P_{bat} - P_{aux}) \qquad (1)$$

$P_{eds}$ Total power fed to electric drive system
$P_{gen}$ Power generated by APU
$\eta_{dcdc}$ Efficiency of DC/DC converters
$P_{bat}$ Battery power
$P_{aux}$ Auxiliary power

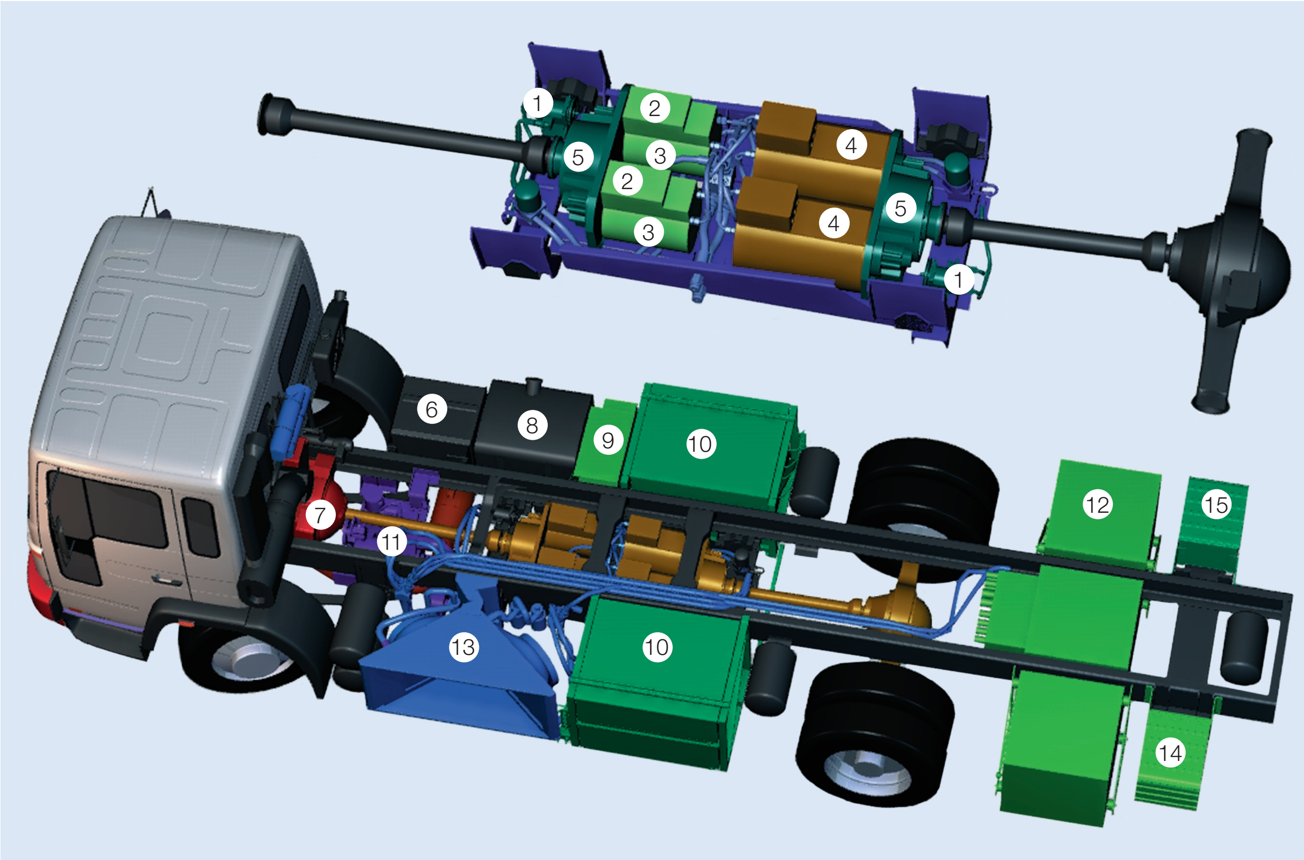
In hybrid mode, the DC bus voltage is controlled such that it always lies between 400 and 650 V DC, depending on the power taken from the generators and their speeds and temperatures.

To limit noise emission when the vehicle brakes at pedestrian crossings or traffic lights, etc, the VMU reduces the speed of the diesel engine and the generator output at speeds below 7 km/h and when the accelerator pedal is not operated. The VMU limits the power taken from the auxiliary power unit (APU) to the range of 0–110 kW.

Battery undervoltage is avoided by gradually limiting the possible power output of the electric drive system whenever the battery voltage becomes too low. Battery overvoltage, which could damage the battery, is avoided by reducing the maximum APU power and the regenerative power from the electric drive system when the battery voltage becomes too high. The system automatically gives priority to the requirements of the electric motor (mainly during acceleration) rather

**Table 2:**
**Specification of the hybrid drive line**

| | |
|---|---|
| Total motor output | 130 kW cont, 370 kW peak |
| Nom battery voltage | 2 strings at 216 V |
| Nom battery capacity | 100 Ah/string, total 43 kWh |
| Total generator output | 110 kW |
| Max diesel engine output | 154 kW at 2,400 rev/min |




***Location of various components in the drive line and chassis of the hybrid truck*** **3**

1 *Oil pumps*
2 *Rectifiers*
3 *Generators*
4 *Motors*
5 *Transmission*
6 *24-V battery*
7 *Diesel engine*
8 *Diesel tank*
9 *Inverters*
10 *Batteries*
11 *Auxiliary power unit*
12 *HV box, with DC/DC converters*
13 *Cooling systems*
14 *12-V battery*
15 *Battery management unit*

than to battery charging. This enables the driver to utilize the vehicle drive systems to the full when the traffic situation requires or allows it.

Regenerative braking, ie braking with the electric motors working as generators and producing electrical energy, is also utilized to obtain the best possible fuel economy.

**Electric motor drive**

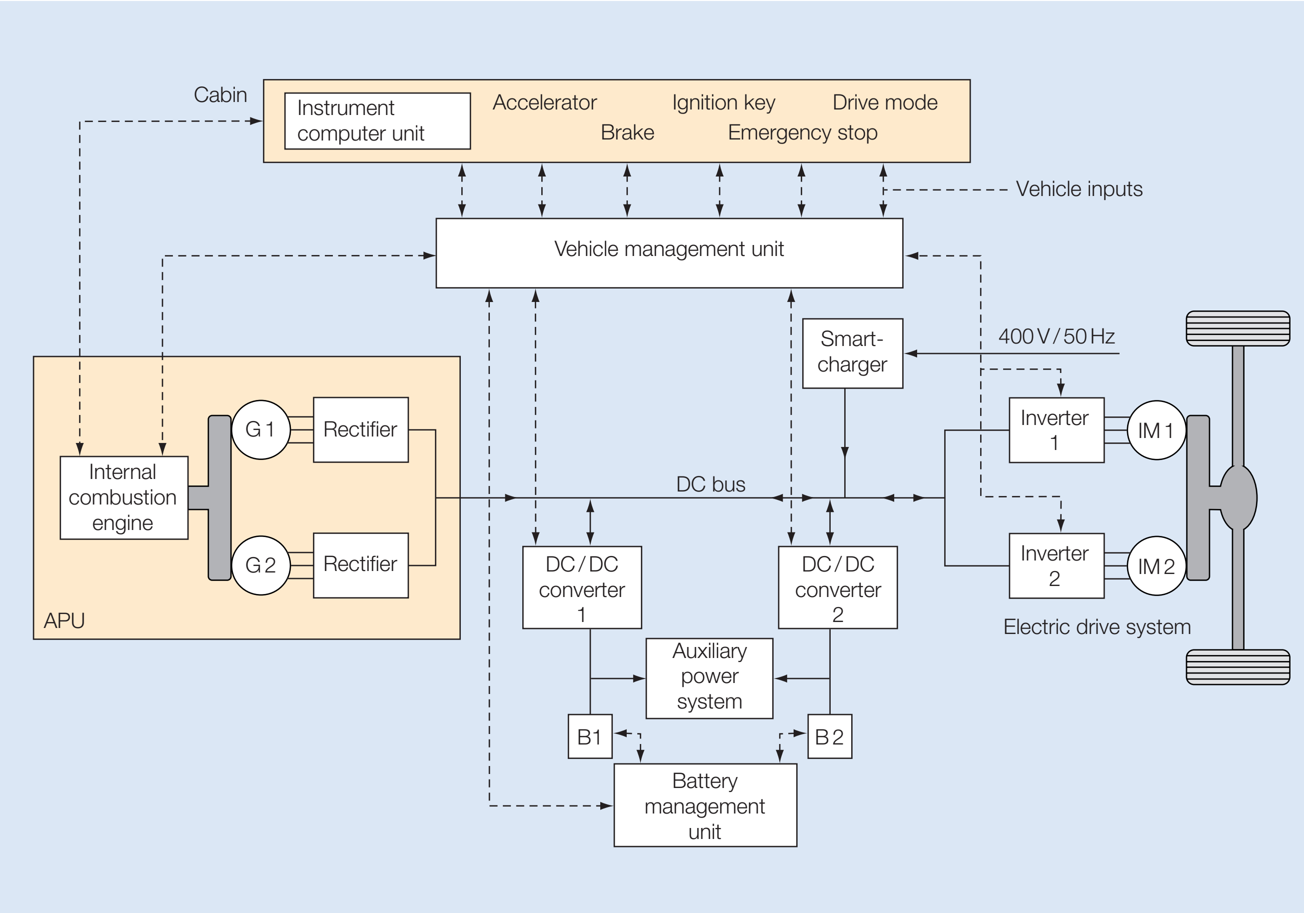
For its propulsion, the truck uses two water-cooled induction motors with inverters. The electric motors act on the rear axle via reduction gearing, a propeller shaft and differential. The total continuous electric motor output is 130 kW. The motors can reach 370 kW momentarily, but are limited in this application by the total power available of around 250 kW.

**5** shows the maximum measured torque and power output values for one of the electric motors when it is coupled to the reduction gear and fed by its converter. The efficiency measured in such a case is shown in **6**. An efficiency in excess of 92 percent is achieved for most parts of the drive cycle. The efficiency of the inverter is steady at around 97 percent, except when the motor speed and torque values are low.

**Battery system**

The installed NiCd batteries weigh 940 kg and have a total energy storage capability of 43 kWh. Water-cooling ensures an efficient working temperature at all times. The batteries are divided into two strings with a nominal voltage of 216 V per string. The DC/DC converters, which connect the batteries to the intermediate DC bus, control the DC bus voltage independently of the actual battery voltage. This enables an optimum working point to be achieved with respect to the APU, so the diesel engine can be operated at speeds that ensure low emissions and maximum efficiency, ie reduced fuel consumption.

The BMU calculates and transmits




***Block diagram of the electrical drive system used in a hybrid truck with diesel engine*** **4**

APU *Auxiliary power unit*
B1, 2 *Battery 1 and 2*
G1, 2 *Generator 1 and 2*
IM1, 2 *Induction motor 1 and 2*

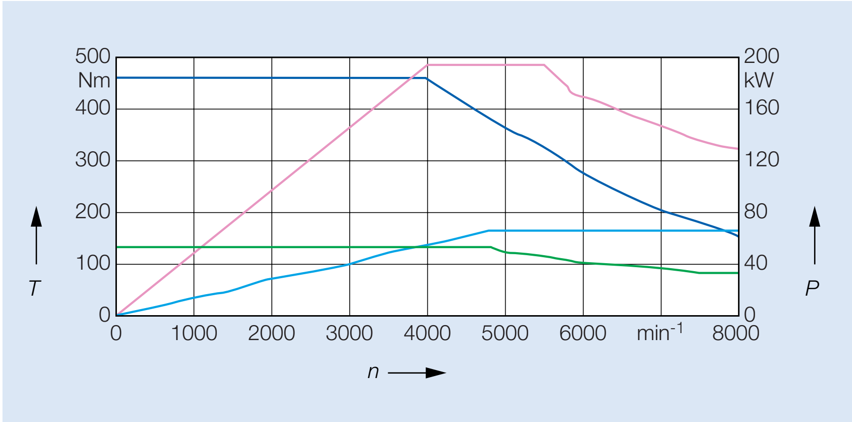
battery limit and reference values to the VMU. Via the BMU, the vehicle seeks optimum running conditions that will not cause the batteries to age too quickly. It also monitors battery charging. An ampere-hour-based algorithm calculates the level of the charge in both battery units. The BMU, which was developed by Volvo, also makes incremental changes possible, so different traffic situations do not cause sudden alterations in the vehicle's performance. For example, battery current limitations due to abnormal battery temperatures are introduced gradually to ensure that there is no sudden change in the motor torque, and therefore in the vehicle's behaviour. The operation of the BMU is shown in **7**.

The vehicle's batteries are charged from the mains by a unit known as the Smartcharger. This is fundamentally an on-board charger, but with the difference that there is no special charging unit on board. Instead, parts of the vehicle's drive line are used for charging from the mains. A 400-V, three-phase terminal rated at a minimum of 16 A is required for charging purposes. Charging begins automatically when the vehicle is connected to the mains and is terminated when the mains lead is disconnected or after the BMU has indicated that the batteries are charged.

**Auxiliary power unit**

The auxiliary power unit is linked to the DC bus via the generator rectifiers. The efficiency of the diesel engine is high and fuel costs are low compared with vehicles with petrol engines. The engine in the trucks now in trial operation is the standard six-liter, six-cylinder, direct injection turbocharged diesel engine used in a conventional FL6. Its maximum output is 154 kW at 2,400 rev/min. The engine is equipped with a continuous regeneration trap (CRT) filter on its exhaust side. This filter reduces the hydrocarbon (HC) content of the gas to about 20 %, the carbon monoxide (CO) content to less than 10 %, and the suspended particles to a quarter of the data for an engine without filter. Another advantage of the filter is that it reduces engine noise.

The generators are water-cooled, three-phase synchronous machines with permanent magnets, and are coupled to the diesel engine via a gearbox. The generators each produce 55 kW at approximately 550 V and 6,000 rev/min, corresponding to a diesel engine speed of 1,700 rev/min). **8** shows the estimated generator output/efficiency curves. The measured values of power output agree closely with the calculated ones. As is seen, the generators work at an efficiency of over 94 percent. Losses in the rectifiers are less than 1 percent.




***Measured maximum output torque T and power P versus speed n for one motor*** **5**

Red *Maximum power*
Light-blue *Continuous power*
Dark-blue *Maximum torque*
Green *Continuous torque*

### Measurements and simulations

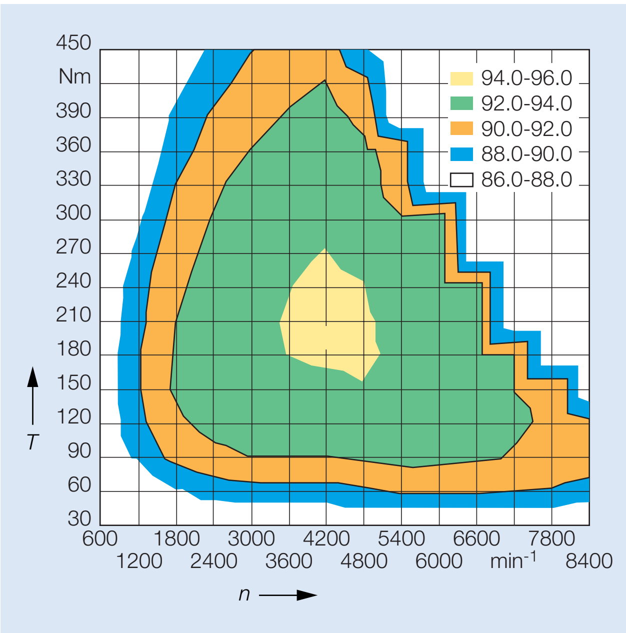
Measurements of the total power output of the electric drive system and the generator and battery output in relation to the vehicle speed in hybrid mode, are shown in **9**. The power from the generator follows the motor load reference value. The batteries are charged by the generators, except when the power needs of the electric motors are greater than can be met instantaneously by the generators. The batteries then supply power, eg to assist acceleration.

### Fuel economy and pollution

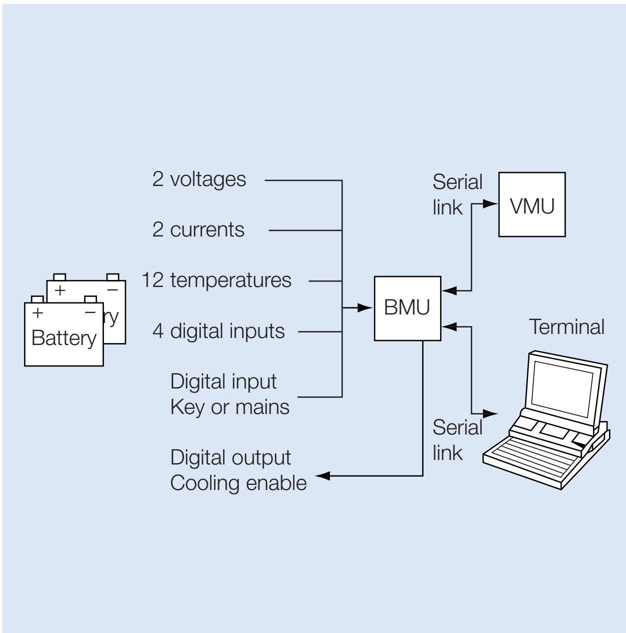
During the specification of the hybrid vehicle environmental considerations were given priority over fuel economy. Volvo has performed simulations that allow a comparison of the hybrid vehicle with a conventional truck in identical city distribution cycles with the vehicles carrying approximately the same payload. **10** shows simulated values of fuel consumption and emissions for a total distance of 71 km (140 km) per day, 15 km of which

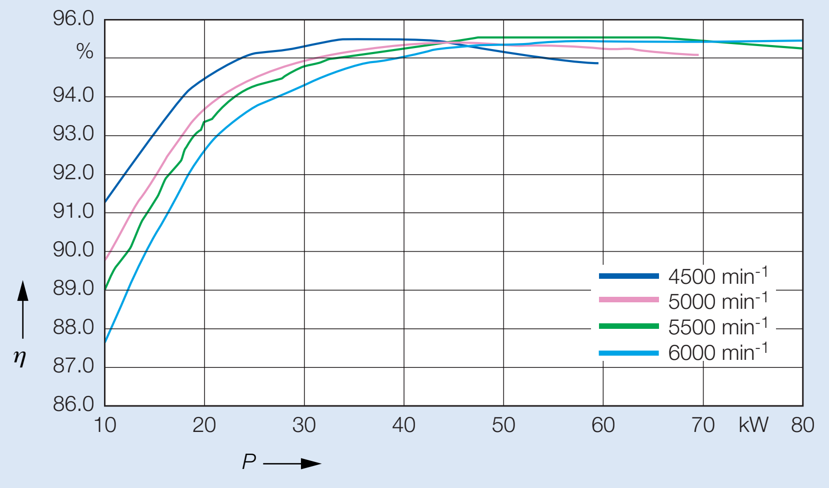
***Measured efficiency (colour chart) of one motor and reduction gear, with the motor fed by its inverter*** **6**

*n* *Speed* *T* *Torque*




***The battery management unit (BMU) calculates and transmits battery limit and reference values to the vehicle management unit (VMU*** **7**





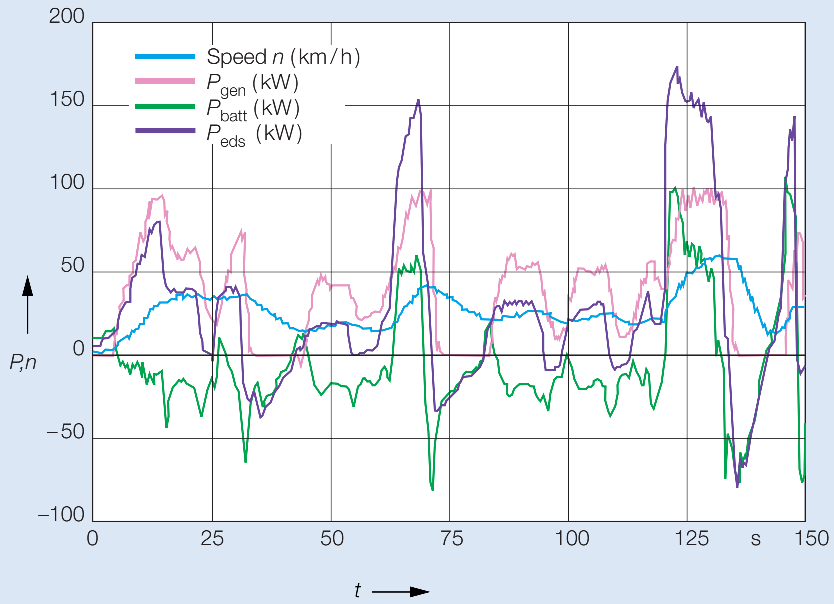

***Generator efficiency η versus power output P, calculated for different speeds*** **8**

are driven in electric mode, with the batteries charged every night with 39 kWh. The calculations show that the fuel consumption and emissions of nitrous oxides ($NO_x$) are lower for the hybrid vehicle than for a conventional truck.

***Vehicle speed n, motor/engine output, battery output and generator output for the Volvo FL6 Hybrid truck*** **9**

*P Output*

*t Time*




**Two main types of hybrid vehicle**

Hybrid vehicles can be divided generically into two types: series and parallel.

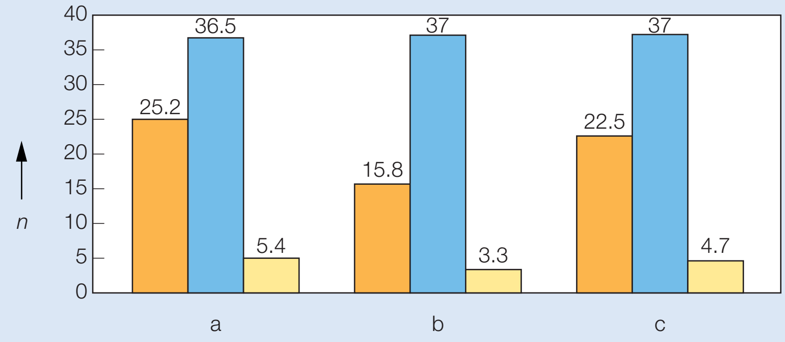
In the series hybrid vehicle the wheels are always driven electrically. The energy sources of this vehicle are some type of internal combustion engine (eg, gas turbine, diesel or petrol engine) and an energy storage unit (eg, in the form of a battery or flywheel). Since the wheels are always driven electrically, the electric motors must be sized for the full performance of the vehicle, taking into account the acceleration and top speed, etc. The IC engine can be sized according to the average power needs of the vehicle, and thus made smaller than if it were to drive the wheels directly. The power balance that every electrical system requires also applies to a hybrid vehicle. In the case of high power demand, the energy storage unit provides the extra power required. When power demand is low and regenerative braking takes place, the energy storage unit can be charged or boosted.

In the parallel hybrid vehicle, the wheels are driven electrically and/or directly by the IC engine, since the electric motor and the engine are coupled mechanically to the vehicle wheels via the same transmission system. Transmission of this type has tended to become rather complicated technically. The energy sources and the means of storing the energy are the same as in the series hybrid vehicle. In a parallel hybrid system, it is most usual for the IC engine to be sized for the full performance of the vehicle, with the electric motor sized for lower performance. The power balance is dealt with in the same manner as in the series hybrid vehicle.

It is not easy to say exactly when a series hybrid vehicle is to be preferred to the parallel hybrid alternative, or how an energy storage unit should be sized. The selection can be based on system simulations, with various requirements taking into consideration, for example:

- Is the range of the vehicle to be given priority over its performance in zero-emission zones?
- Under what environmental conditions (environmentally sensitive zones, night-time driving, etc) are the vehicles to be driven?

The series hybrid solution has been chosen for the system supplied by ABB Hybrid Systems, since the demands of operation with zero emissions are stringent (the vehicles are to run in distribution service with loading and unloading in the city center) and since the vehicles will not be run for long distances on highways. The zero-emission requirement also means that the batteries are sized according to the energy demand (vehicle range) rather than the power requirement (additional power), but without cutting back on the acceleration requirement.




***Comparison of simulated values for emissions and fuel consumption for a conventional Volvo FL6 truck and a hybrid truck built on the same chassis. Driving is simulated for typical distribution services in a built-up area.*** **10**

a *Standard Volvo FL6, 11,000 kg*
b *Volvo FL6 Hybrid, 14,000 kg, 71 km/day, charged with 39 kWh per night*
c *Volvo FL6 Hybrid, 14,000 kg, 140 km/day, charged with 39 kWh per night*

*n* *Speed in km/h*

*Orange* *Fuel consumption (liters/100 km)*
*Blue* *Mean speed (km/h)*
*Yellow* *$NO_x$ emissions (g/km)*

**Summary and outlook**

A development goal of the hybrid truck was to base the solution on a standard vehicle equipped with an electrical drive line from ABB.

In hybrid mode, the diesel engine is operated at speeds that afford optimum efficiency (ie, fuel consumption) and low emissions. Also, in hybrid mode the vehicle's average power requirement is generated by the APU and the surplus power charges the batteries. Whenever higher output is needed, the batteries provide the extra power.

Simulations show that fuel consumption is lower and emissions considerably lower with the hybrid truck than with a conventional vehicle. The possibility of running the truck entirely without emissions is a further environmental benefit.

The two hybrid trucks used for the three-year trial will provide valuable data based on commercial distribution service and real-world traffic conditions. One of the purposes of the trial is to evaluate customer acceptance of the new technology. In addition, the experience that is gained will point to any parts of the hybrid system that may need to be improved.

The additional weight of the vehicle compared with a conventional Volvo FL6 is slightly more than 3 tonnes. This is due to the extra weight of the drive line, including the batteries. In the long term, this weight will be reduced as the components are further developed.

The Volvo FL6 Hybrid has a total load capacity of about 5 tonnes. The additional weight of the vehicle has no effect on the payload volume, so that the vehicle offers unrestricted load capacity for a distribution vehicle.

Today, the electrical drive line is expensive, but this is largely due to the fact that its components are produced in a small series. With mass production, these costs will be considerably reduced, and studies indicate that the price of an electrical drive line in the future will not be higher than that of today's conventional drive systems.

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[1] P. Chudi, A. Malmquist: A hybrid drive for the car of the future. ABB Review 9/93, 3–12.

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**Author's address**

Niclas P. Berg
ABB Hybrid Systems
S-721 67 Västerås
Sweden
Telefax: +46 21 34 01 91
E-mail:
niclas.p.berg@sehyb.mail.abb.com

**Major rectifier package for extension to aluminium smelter in Dubai**

The *Dubai Aluminium Company* (Dubal) has selected ABB Industrie AG, Switzerland, to deliver the rectifier package for the new potline no. 6 at its aluminium smelter complex at Jebel Ali. The value of the contract is US$ 18 million.

The rectifier package consists of four 55-kA units rated at 1,300 V. ABB Industrie AG is also delivering the DC busbars, the protection and control equipment and the necessary ancillaries, and will further be responsible for the site coordination and commissioning.

ABB Environmental AS of Norway has been awarded the turnkey contract for the fume treatment plant.

The new production line, with 240 pots, will increase the capacity of the smelter by 135,000 t per year. Commercial start-up is scheduled for mid-1999. The expansion will make Jebel Ali the second-largest smelting operation in the world. Since 1989 ABB Industrie AG has equipped all new lines built by Dubal with electrical systems, adding up to total deliveries worth US$ 90 million.

**500-MW gas turbine power station with desalination plant**

ABB has received a turnkey order to build a 500-MW gas-fired power and desalination plant in Abu Dhabi, United Arab Emirates. The total value of the order, which was placed by *Abu Dhabi National Oil Company Ltd* (ADNOC), amounts to about US$ 600 million. The new facility will be located in the coastal industrial area of Ruwais.

The project is planned to expand ADNOC's Ruwais Refinery General Utility Plant and the company's refining and petrochemical capacity by increasing the amount of available electricity to 700 MW. The desalination plant will also supply up to 8 million gallons of water per day to the refinery.

Under the terms of the contract, ABB will supply four GT13E2 gas turbines and generators, along with the heat recovery steam generator and the desalination plant. ABB will also provide the overall power plant control system, the balance of plant equipment and the complete engineering, installation and commissioning work. Full commercial operation of the plant is expected by the year 2000.

**ABB wins orders worth US$ 170 million for Brazil power link**

ABB has been awarded contracts worth a total of about US$ 170 million to link the power grids of northern and southern Brazil.

The contracts, which were awarded by the state-owned utilities *Furnas Centrais Eléctricas S.A.* (FURNAS) and Centrais Eléctricas do Norte do Brasil S.A. (ELETRONORTE), are part of the 'Brazil in Action' infrastructure development programme launched by the federal government to support the country's future economic growth.

The ABB orders include a 300-km, 500-kV AC transmission line, high-voltage equipment for 5 substations as well as 6 reactive power compensation units.

The new power link will bring southern Brazil electricity from the northern part of the country. The overall project is expected to be completed by 1999.

**ABB equips two Greek cruise liners with electrical equipment**

*Blohm + Voss* of Hamburg has awarded ABB Industrie AG, Hamburg, a contract to supply the electrical equipment for two cruise ships. The value of the order is well in excess of US$ 20 million.

ABB will be responsible for planning and supplying all the electrical installations, including the switchgear and automation equipment, navigation systems, lighting and the communications and entertainment systems.

The cruise ships are being built for the Greek shipowner *Royal Olympic Cruises*. They will begin commercial operation in the eastern Mediterranean in June 2000 and March 2001, respectively.

**Ten rectifier packages for an aluminium smelter in Canada**

ABB has received an order from *Société d'électrolyse et chimie Alcan* in Alma, Canada, to deliver 10 rectifier systems and a 161-kV high-voltage installation for the planned expansion of its aluminium smelter. The order value for Asea Brown Boveri Inc, Montreal, is about US$ 47 million.

Ten 97-kA rectifier systems rated at 1,330 V and worth US$ 12 million will be built by ABB Industrie AG in Switzerland. The total power output of approximately 1,290 MW represents the highest rated power supply ever built for an aluminium smelter.

The installations will be delivered, installed and put into operation by ABB in 1999 and 2000.

**ABB to refurbish Icelandic and Swedish hydropower plants**

ABB Generation AB, Sweden, recently received three orders for refurbishments of hydropower plants. The total value of the orders is approximately US$ 12 million.

*Landswirkjun*, Iceland, has ordered electrical components for the 210-MW

Búrfell hydropower plant, which was built in 1970 in south-east Iceland and supplies Reykjavik with electrical energy.

*Gullspång Kraft AB*, Sweden, has placed an order with ABB Generation for components for the modernization of the electrical equipment and control systems in the Dönje and Blåsjön hydropower stations.

The third order is from *Vattenfall AB*, Sweden, and involves control equipment for the Rusfors power station.

**Advanced switchgear production facilities**

With a total investment of some US$ 40 million, ABB Calor Emag Schaltanlagen AG has built a new factory in Ratingen, Germany, equipped with advanced systems for the manufacture of high-tech switchgear products. Also new is the organization of the production process, which includes plans to locate supplier companies in premises on the works site.

The new plant will begin production in September 1999, after which complete medium-voltage substations as well as high-tech switchgear components will be manufactured there. The production of vacuum interrupter chambers, which are the centerpiece of ABB Calor Emag-built circuit-breakers, is to be increased from 60,000 today to 100,000 units per year. The modern, cost-saving production methods will ensure that these interrupter chambers remain competitive on the world market in the future.

**220-kV outdoor substation in Egypt built to ultra-tight deadline**

Recently, a 220-kV outdoor substation for the Egyptian steelworks *Al Ezz* was successfully taken into operation just 11 months after signing of the contract.

The turnkey substation, with a value of US$ 7.5 million, was built by a consortium comprising ABB Calor Emag Schaltanlagen AG, Germany, ABB High Voltage S.A.E., Egypt, and ABB Trasformatori S.p.A., Italy.

The key factors behind the Egyptian steel company's choice of vendor were quality, experience and an ultra-tight delivery deadline: 12 months at most were available for planning, building and commissioning of the 220-kV substation. The double-busbar installation consists mainly of two transformer bays, four feeder bays, one coupler bay, power transformer, protection and control equipment, auxiliaries and communication equipment.

**ABB wins US$ 160 million contract for subsea oil installations**

ABB has been awarded a contract to build complete subsea installations for the Snorre B oilfield development on the Norwegian continental shelf. The contract, awarded by *Saga Petroleum ASA*, Norway, amounts to US$ 160 million and includes options for future expansion valued at an additional US$ 100 million.

Snorre B is located in the northern part of the Snorre field, at a depth of 350 m. Work will commence immediately.

Under the terms of the contract, ABB will be responsible for the engineering, procurement, contracting and installation work. Deliveries include four templates with manifolds, wellhead, trees and control systems for 27 subsea wells as well as control umbilicals. ABB's modular subsea system technology allows Snorre B to be developed more cost-efficiently, safer and faster than with conventional technology.

**Advant to control world's largest waste incinerator**

A contract has been won by ABB Kraftwerksleittechnik GmbH, Germany, to supply and install the instrumentation and control systems for the first 6 units of the new TUAS South waste incineration plant in Singapore. The turnkey plant is being built by Mitsubishi Heavy Industry (MHI) of Japan for the *Ministry of Environment* in Singapore and will consist of six boilers, each with a capacity of 720 t/day commercial and domestic waste, as well as two 65-MW steam turbines. Hand-over of the plant is scheduled for March 2000.

After Ulu Pandan, Senoko and TUAS 1, TUAS South is the fourth waste incineration plant to be built in Singapore. A key factor in winning the contract was ABB's ability to provide a complete electrical and control package. The electrical components are being supplied by various ABB companies in Europe and Singapore.

TUAS South will have an ergonomically designed control room with many user-friendly features. An oval arrangement of the workstations and three large-screen displays, etc. offer an excellent overview of the complete plant. A video system consisting of 33 monitors and 40 cameras will be installed to watch over the waste storage pits and weighing stations.