Intelligent GIS – a fundamental change in the way primary and secondary equipment is combined

New technologies are constantly being introduced to the GIS substation sector with the aim of reducing total life cycle costs, improving reliability and minimizing environmental impact. They are based on modern integrated control and protection systems, innovative sensors and the latest developments in the primary hardware area.

Traditionally, a substation's high-voltage apparatus and its control and protection equipment have been treated as separate systems. The interfaces between these systems are defined on the level of the hard-wired connections that link the electronics to the primary hardware. Given the technical maturity of the primary equipment and the numerical control and protection systems, it is possible today to achieve a substantial improvement in functionality as well as overall cost benefits by mutually integrating the two technologies. This development is being further stimulated by the growing pressure on utilities to reduce costs, and increasingly by environmentally motivated restrictions, which are holding up grid extension programmes.

Due to the good availability and proven performance of numerical station control and protection systems, it can be expected that the traditionally heavy and expensive current and voltage transformers as well as the electromechanical tripping relays and contacts will be replaced by low-cost sensors and electronic actuators. As a result, the A/D conversion units and some intelligent preprocessing functions that are now located in the control cubicles will be decentralized, in some cases as far down as the process level. The hard-wired connections between the process and the control equipment will be replaced by optical fiber buses.

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Deregulation and its consequences for the utilities

Globalization and the opening of the world's markets are intensifying the competition between power suppliers. As industries strive to become more competitive, greater pressure is being put on the price of electrical energy. One result of this is that many utilities are being forced to deregulate and rethink their cost management strategies. New installations are consequently being evaluated not only on the basis of the first-time costs but also on the expected total costs over their life cycle.

In line with this development, suppliers of electrical equipment are having to offer new, innovative solutions and at the same time make use of the latest technologies to ensure cost-efficient operations.

A look is taken in the following at the kind of changes that can be expected in the field of gas-insulated substations (GIS). The new technologies are also highlighted, especially those in the secondary systems, and their benefits for the users.

Integration of secondary technology in GIS

In gas-insulated substations, as in other kinds of technical plant, a clear distinction is made between the primary and the secondary equipment **1**. The GIS primary equipment consists of the high-voltage apparatus that performs the primary functions of the substation, such as switching, short-circuit current interruption, measurement and isolation.

The term 'secondary technology' covers all the individual components that make up the protection, control and measuring equipment.

Both the primary and the secondary equipment have today attained a high level of technical maturity and operational safety. One way of obtaining a major improvement in functionality as

Example of a modern 300-kV gas-insulated substation with integrated cubicle for the control and protection equipment **1**

well as cost benefits is to merge the two technologies. This development is also being encouraged by the growing pressure on utilities to lower costs and by environmental constraints, which are slowing down the extension of existing power transmission networks.

Three consecutive phases define the merger of the primary and secondary technologies **2**:

- Conventional technology
- Modern technology
- Intelligent GIS

Conventional technology

Electromechanical relay technology has been largely responsible for the conventional layout of the secondary part of a substation. In this technology a large number of different devices, each one developed for a specific application, is interconnected by copper wires in order to fulfil all of the control, protection and measuring functions. These devices were mainly built into cubicles located in a separate room next to the GIS. In the GIS bay itself there was another cubicle that contained several relay switches for simple bay interlocking and local control functions. As many as several thousand connecting wires between the GIS and the local cubicle, as well as between the local cubicle and the main control and protection cubicles, had to be planned and installed. For some of the connections, such as those to the current and voltage transformers, special attention had to be paid to the type and length of the wires to ensure the required measurement accuracy.

Electromechanical protection relays as such achieved a very high level of accuracy and safety providing regular maintenance and adjustments were carried out. In time, some of their protection functions were performed by static relays. Although these were not able to match the high stability and reliability of the electromechanical relays, they offered more functionality. At a later stage, the static relays were replaced by digital relays. Steady improvement of the digital electronics and the introduction of self-supervision routines have meanwhile resulted in modern digital relays becoming even more reliable than the conventional electromechanical types.

Eventually, these numerical relays became capable of performing different protection and, later, control functions on the same hardware systems. It has been this technological re-orientation that has allowed the layout of the secondary equipment of a gas-insulated substation to be considerably simplified.

Modern technology

As mentioned above, the progress made in the field of digital electronics allows most of the functions of the secondary equipment to be performed by means of software modules running on the same computer-based devices. These digital, multi-functional units can be used for control as well as for protection and other secondary functions. Because of this, it is possible to group and combine different functions using just software tools. Whereas conventional relay equipment was developed for one specific application, modern digital devices are able to handle a multitude of functions in parallel. In the case of GIS – although it applies in a similar way to AIS as well – this offers the advantage of compact solutions for the entire protection and control system. In recent years, this opportunity was taken advantage of to integrate the secondary bay equipment of a GIS in the local bay cubicles, which had traditionally been equipped with just the hard-wired interlocking equipment for the bays. The communication between the bays themselves and between the bays and the substation control computer is established by a small number of serial fiber optic buses that replace the traditional hard-wired single signal connections. This technology is available and has been successfully introduced to the market. A modern integrated bay with control and protection cubicle is shown in **3**.

Advantages of the modern technology are:

- A substantial reduction in the number of components used to perform the same functions.
- The hardware required for the bay-oriented control, protection and measuring functions can be built into the local control cubicle. An additional room for the secondary equipment is no longer needed.
- Reduction or elimination of parallel wiring between the bay and the station level due to the use of fiber optic communication buses. As a result, project engineering can be simplified and EMC problems are less severe.
- Increased availability through self-supervision and self-checking of the electronics for the remaining hard-wired connections between the control cubicle and the primary hardware as well as checking of the function of the tripping circuits.

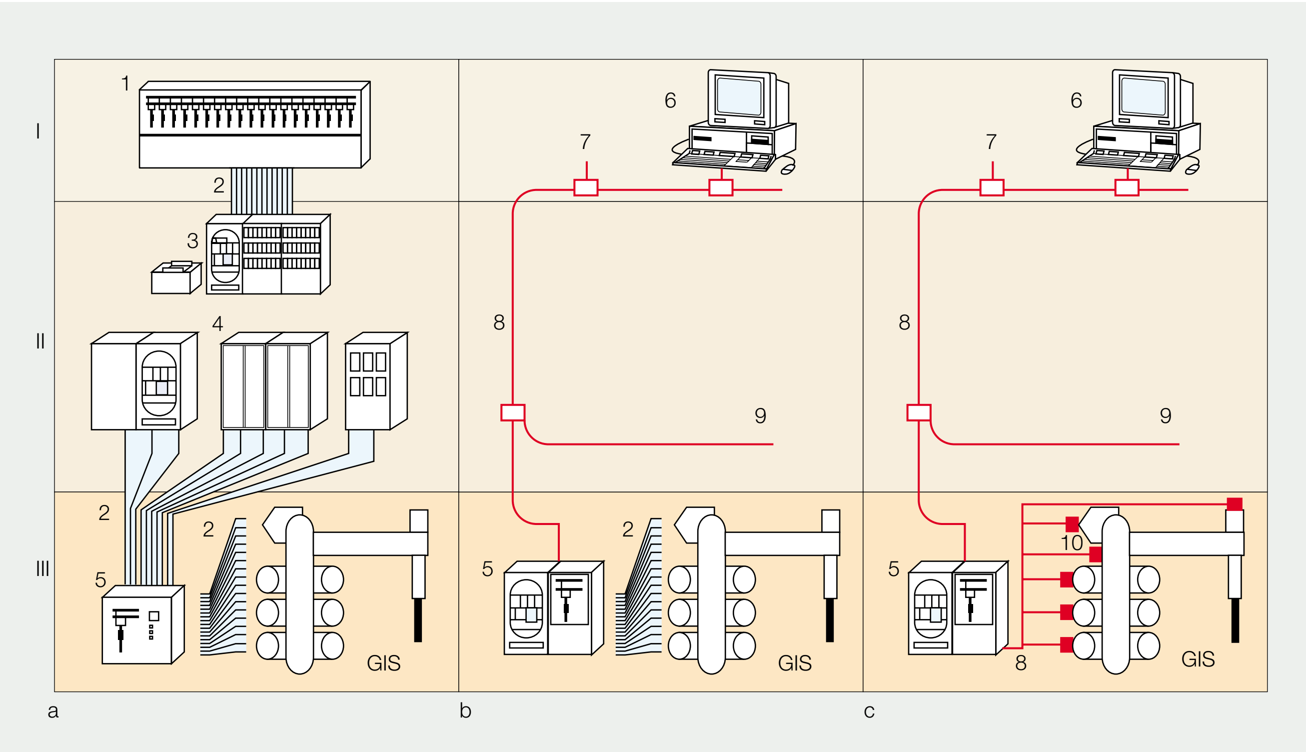
Phases in the development of secondary equipment in gas-insulated substations **2**

a Conventional technology
b Modern technology
c Intelligent GIS

I Operating room
II Relay and ancillaries room
III Switchyard

1 MMI and control board
2 Hard-wired connections
3 Event recorder and protection
4 SCADA: distribution and metering
5 Bay cubicle
6 Man-machine interface
7 Gateway

8 Serial data link
9 To other bays
10 Sensors and actuators



A drawback of modern integrated secondary technology is the continued presence of hard-wired connections between the bay cubicle and the primary components of GIS. ABB has therefore developed a serial optical bus system to replace these connections.

Intelligent GIS

The introduction of a serial fiber optic connection between the local control cubicle and the GIS primary equipment (process bus) will cause a shift in the traditional borderline between the primary and the secondary part of substations. The A/D conversion units and some intelligent preprocessing functions which are currently located in the electronics cubicles will be decentralized as far down as the process level and physically integrated into the primary components 2, 3.

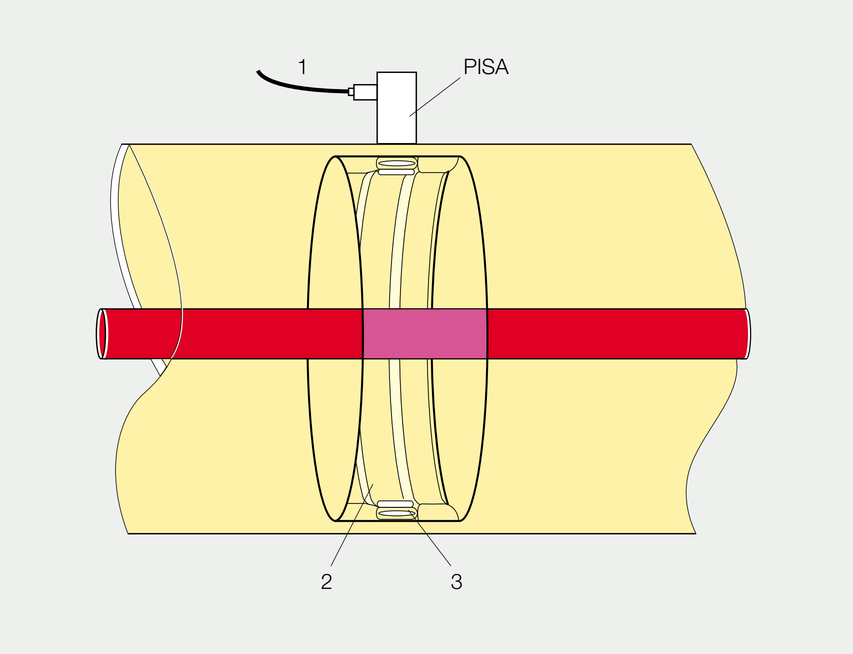
Besides allowing simple replacement of the hard-wired connections to the primary equipment – a simplification which translates into reduced costs – this significant innovation is needed to respond to increasing demand for monitoring, diagnostics and automatic maintenance scheduling functions. Also, modern sensor technology can be used for the primary apparatus, such as drives, auxiliary position indicators, current and voltage transformers, etc. Hitherto, these components have been trapped in an outdated technology, making them increasingly expensive to manufacture and maintain.

The serial process bus concept with distributed electronic process interfaces integrated in the primary hardware allows a well-structured and modular approach to the merging of the primary and secondary equipment in a substation. The process and hardware realization of the data acquisition, monitoring, diagnostic and other interface functions depend on the technology used in the primary equipment and will determine the design of the corresponding process interfaces 13. On the other hand, the communication via the serial bus between the different process interfaces and the devices for protection and control located in the bay cubicle, which are on a hierarchically higher level, will be standardized. The standardization of the process bus communication is intended to allow equipment from different vendors to be interconnected, thus enabling utilities to make savings on their capital investments.

GIS bay with modern integrated control cubicle 3

Sensors replace current and voltage transformers

The replacement of conventional current and voltage transformers by sensors is among the most obvious advantages of intelligent GIS. As a result, high-power input signals are not needed for numerical control and protection equipment. Low-voltage signals with small current values are sufficient, so that heavy and expensive instrument transformers can be replaced by low-power, compact sensing devices. Many significant difficulties with the traditional measuring systems can then be eliminated direct.



Combined UI sensor for GIS with electronic interface (PISA) **4**

1 *Serial optical fiber link*
2 *Voltage sensor*
3 *Rogowski coil*

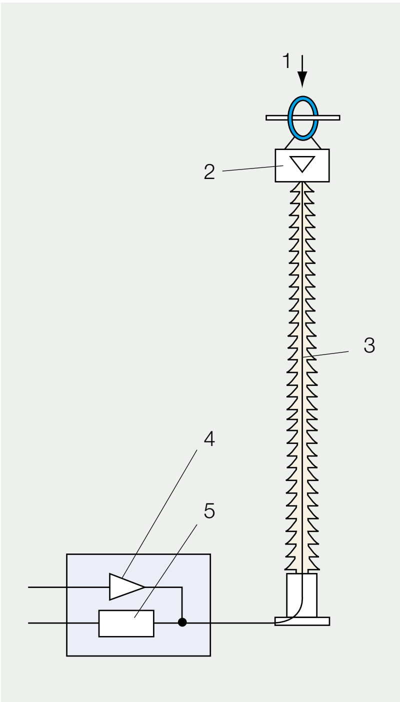
Difficulties with conventional instrument transformers

Conventional current and voltage measurement transformers have the following drawbacks:

- Their design is based on the requirements of electromechanical relays. The high input power requirements of these protection devices (up to 60 VA and 5 A) have led to large physical sizes for the measurement transformers and, as a result, high costs.
- To meet the accuracy class and stability requirements of the measurement system, special attention has to be paid to the connecting leads between the measurement transformers and the relays.
- Measurement and protection applications call for very wide dynamic ranges for the electric signals. The saturation of the transformer cores limits the dynamic range of conventional instrument transformers. Therefore, different CT cores and VT taps have to be provided for the different applications in the secondary systems. Because of this, the systems for measurement, metering and protection have traditionally been treated separately.
- The saturation of the current transformer cores that takes place at high short-circuit current levels distorts the measured current signal. Complicated and expensive protective devices are needed to reshape the distorted signal and allow proper operation of the protection systems.
- High overvoltages due to ferro-resonances excited by the non-linearity of measurement transformers have repeatedly caused damage to nearby station equipment. While this effect is well known, it is difficult to avoid completely. One of the key tasks of substation project engineers is therefore to assess this effect and provide remedial measures. For example, the grading capacitors of circuit-breakers can be adjusted to the surrounding equipment to limit its consequences.
- Because of their complex dielectric structure, voltage transformers represent a weak point in the dielectric insulation of the transmission system. They are therefore responsible for a significant proportion of the flashovers occurring in the transmission grid. It has to be acknowledged, however, that this situation has improved through the efforts of the voltage transformer manufacturers.

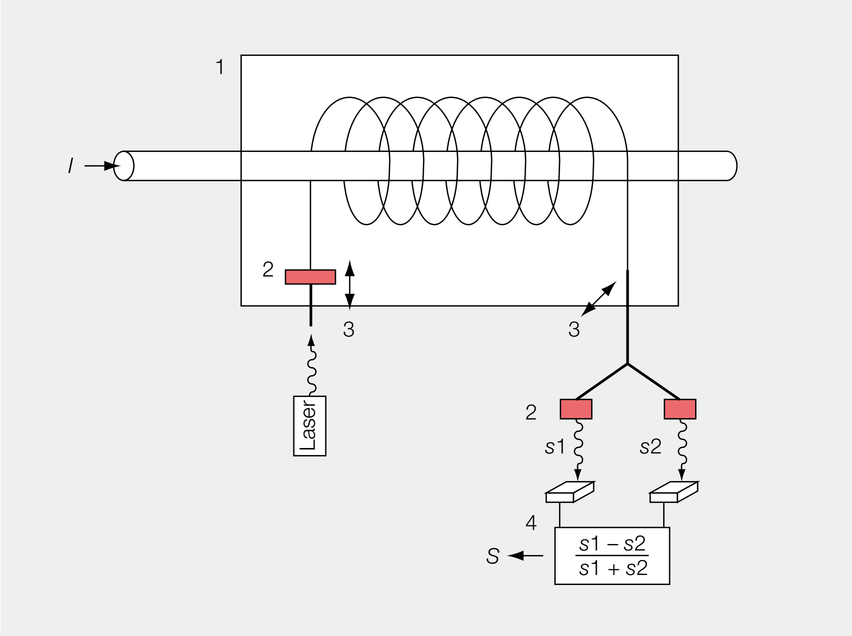
Air-insulated current sensor with electronics located at HV potential supplied with power by a laser light **5**

1 *Conventional core transformer or Rogowski coil*
2 *Electronic box for conversion to optical signals*
3 *Optical fiber for signals and optical power supply*
4 *Optical power supply for electronics located at HV potential*
5 *Electronics for signal processing*



Alternative methods of measurement

Given the drawbacks of conventional instrument transformers and the maturity of the numerical protection and control equipment, alternative measurement devices featuring sensors were developed and tested in long-time field trials. The novel sensors are based on various physical principles. Some of them are already available as products, but their application range is still limited due to the lack of an integral and consistent station control system approach. There are two basic categories of physical principles for the current and voltage sensors: the first category (semi-conventional) is based on conventional electromagnetic measurement techniques but with a strongly reduced power output compared with today's current and voltage transformers; the second category is based on other kinds of physical effects, usually of an optical nature.



Principle of operation of an optical current measurement sensor **6**

1 *Optical fiber sensor*
2 *Polarizer*
3 *Angle of polarization*
4 *Photodiodes*

I *Current*
S *Light intensity*

Sensors based on semi-conventional electromagnetic measurement principles

The first category of semi-conventional current and voltage sensors is based mainly on the traditional inductive, capacitive or resistive sensing technique, although with a low power output. This technique provides optimum solutions where there are short insulation distances between the high and the ground potential, as in the case of GIS and medium-voltage equipment. In high-voltage applications with air insulation, it is difficult with the semi-conventional technologies to bridge the insulation between the high and the ground potential with the measured signal. However, solutions based on electromagnetic sensors also exist for air-insulated equipment.

Due to the reduced power of the semi-conventional sensors, the electronic interface (PISA) between the sensor and the data processing units is included or even completely integrated in the hardware.

Combined current-voltage sensor

A combined current and voltage sensor has been developed to replace the conventional current and voltage transformers in GIS. The current sensor is based on a Rogowski coil (a coreless inductive current transformer). The voltage sensor is based on a capacitive electrical field sensor **4**. Since the Rogowski coil has a linear characteristic, saturation does not have to be taken into account for the protection algorithms. The capacitive ring, which acts as a voltage sensor, also has a linear characteristic and is very simple in terms of the insulation. This solution, including the integrated electronic interface (PISA), will be explained in more detail later.

Digital optical instrument transformer for AIS

Sensors with reduced cores or coreless sensors based on the Rogowski coil principle have also been developed for live tank current measurement applications. They have been in use for several years, but in a limited application range.

The cost-saving potential of sensors for air insulation is a result of the simplification of the insulation system. One solution **5** has been to put the electronic interface close to the current sensor located at HV potential and to transmit the measured signals from the high potential to ground potential by means of an optical digital signal. The power for the electronics located at high potential is supplied either by magnetic or capactive stray fields or optically by means of laser light through an optical fiber coming from a laser diode at ground potential.

Sensors based on other physical principles

This second category of current and voltage sensors is based on the direct optical effects of electrical and/or magnetic fields. Therefore, there are no insulation problems with these sensors in high-voltage air insulation applications either. This technology is most likely to be the winner in the field of air-insulated equipment.

Faraday effect for current sensing

Magnetic fields influence the polarization angle of polarized light. The change in the polarization angle is directly proportional to the magnetic field. By measuring the change in the polarization angle of light fed into an optical fiber coil around a current conductor it is possible to calculate the current flowing in the conductor **6**, **7**. The accuracy is sufficient to meet even metering requirements. Optical current transformers of this type are commercially available today.

Piezo-optic effect for voltage sensing

Electric fields influence the physical size and shape of piezo crystals. This influence can be measured, for example, by means of an optical fiber wound around such a crystal **8**. Since the effect is also directly proportional to the electric field in the crystal, the voltage applied to it can be measured accurately.

A prerequisite for the successful market introduction of sensors based on direct optical effects is an optimum interfacing technology between the sensor and the station protection and control system. Like the Rogowski coil and the capacitive sensor in the case of GIS, direct optical sensors have the potential to be fully integrated physically into other equipment (eg, circuit-breakers) in HV air-insulated substations, thus offering a substantial economic advantage over conventional current and voltage transformers.

Since GIS is setting the trend for combined primary and secondary technologies, the system solutions that are currently in the final stages of development are presented in more detail below. Sensors form an important part of the intelligent GIS concept.

Concept of intelligent GIS

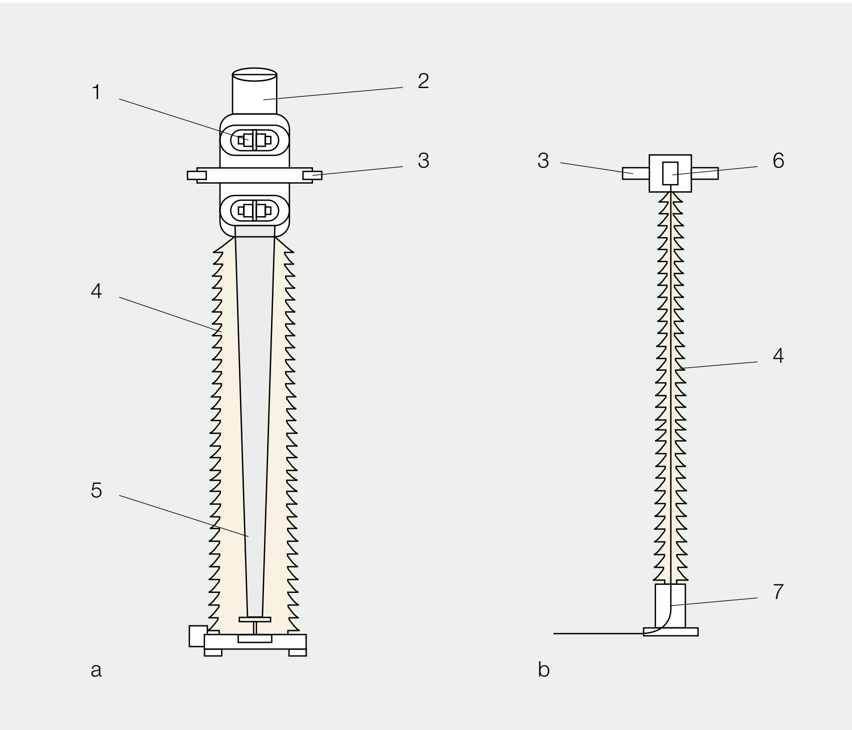
The concept of intelligent GIS is shown in **9**. Its characteristic features are:

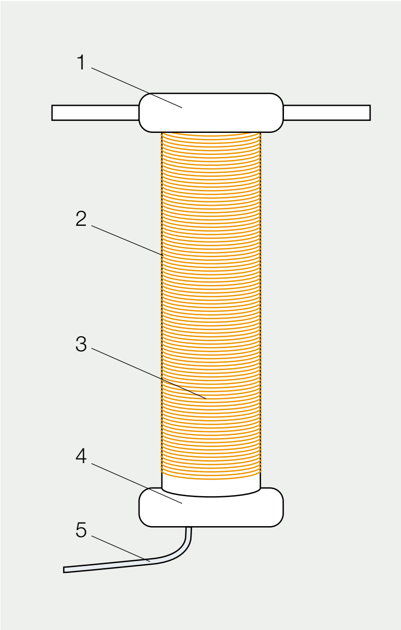
- All the primary components are connected to the bay cubicle by means of a serial optical fiber bus. Conventional hard-wired connections are eliminated.
- Each primary device (sensor and actuator) is equipped with an electronic interface dubbed PISA (for Process Interface for Sensors and Actuators). The main tasks of PISA are the analogue to digital conversion and preprocessing of measured signals, the correct transmission of the converted serial messages to the bus and the execution of control or protection commands sent via the serial bus. Further duties may be the local storage of data for the fault recording function of the Station Control System (SCS), some device-specific monitoring and diagnostic functions and intelligent switching functions, such as point on wave switching for circuit-breakers.
- As in a modern SCS **2**, the control and protection devices of the intelligent bay are located in the local control cubicle. Certain device-specific monitoring and diagnostic functions

Comparison of a conventional live tank current transformer with an optical sensor **7**

a Conventional current transformer
b Current sensor

1 Secondary winding and transformer core
2 Oil expansion vessel
3 HV current connection
4 Insulator
5 Insulation for secondary winding
6 Optical sensor head
7 Optical fiber





Optical voltage sensor **8**

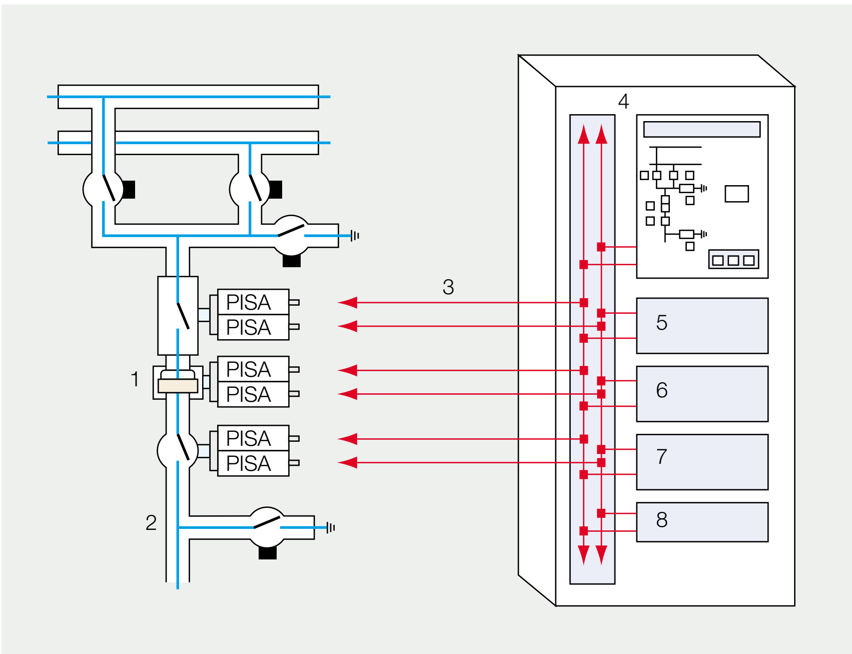
1 *High potential shield*
2 *Quartz*
3 *Optical fiber wound around quartz crystal*
4 *Ground potential shield*
5 *Optical fiber in/out*

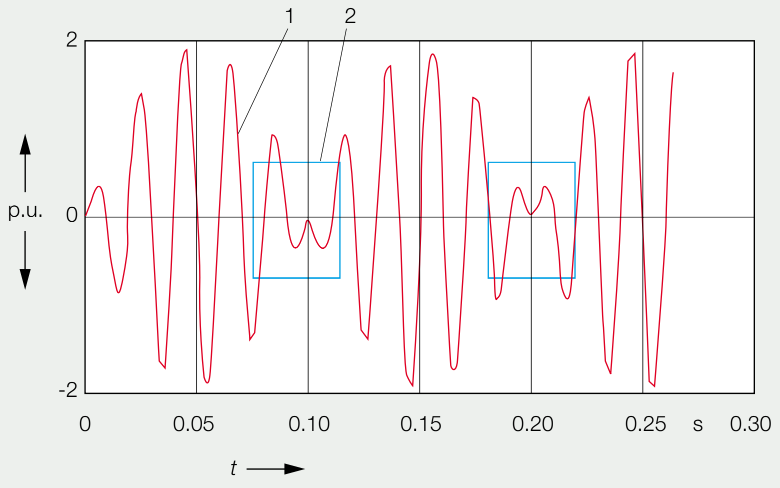
can be distributed at the process level or are assigned to the PISA interface. The control and protection devices in the bay cubicle receive the sensor signals via an optical fiber bus (process bus) instead of hard-wired connections.

- The signals from the sensors and actuators are transmitted to the bus once only and are available to all the devices and for every function needing the information. This is one of the most important differences between intelligent GIS and the conventional technology.
- Today, most of the control, protection, measurement and metering devices are connected via separate measurement lines to specific transformer windings or taps. This is mainly due to the fact that these devices need function-specific input power and operate on different signal levels. The saturation of the transformer cores limits the dynamic range. Since it is coreless, the new sensor substantially increases the dynamic range of the measurement. Thus, one sensor is sufficient for all types of measurement. As a result of this simplification, true redundancy concepts are possible.
- The process bus between the PISA interface and the bay units performs in true real time. This is of great importance, as the tripping and current/voltage signals which are transmitted on the bus are required for protection and interlocking functions. A prerequisite for this is that the time scatter between the devices in the bay and the PISA interface is sufficiently small.
- An IEC working group is engaged in standardizing the communication protocol of the process bus. The goal of such an open bus concept is standard process bus communication that will enable equipment from different vendors to be connected via the PISA interface.
- Devices which are not compatible with the standard process bus can be connected to the system by means of an interface.
- In the case of GIS, the power for the PISA interfaces is supplied over copper leads located in the same cable as the optical fibers of the bus.
- To obtain true redundancy the PISA interfaces and the bus connections between the interface and the local control cubicle can be duplicated. Therefore, each critical item of apparatus can be equipped with two identical interfaces and bus connections, each of which supervises the other. In the event of a failure in one of the devices, the other assumes full functionality. An alarm is generated and the defect can be repaired or the cir-

The intelligent GIS bay **9**

1 *UI sensor*
2 *GIS primary hardware*
3 *Redundant serial optical process bus*
4 *Local control and protection cubicle*
5 *Control back-up protection*
6 *Main protection*
7 *Metering*
8 *Interface to other systems*





Intelligent switching, here involving compensated lines **10**

1 *Voltage across circuit-breaker*

2 *Optimal closing instants*

cuits replaced easily without interrupting operation in any way.

- Communication between the individual bays and between the bays and the station computer is also via a bus **2**. Ideally, this bus will be of the same type as the process bus. In this way, the real-time communication between the bays – for example, for the inter-bay interlocking – can also take place over the optical serial bus.

Functional advantages of the intelligent GIS

Monitoring and diagnostic functions of the PISA interface

Since all of the switching and measuring devices of the primary equipment are equipped with a process interface (PISA) and the computing power is available directly at the process, monitoring and device-specific supervision functions are now possible which were previously either not feasible or were very expensive to realize. The system concept of the intelligent GIS is a prerequisite for the economical introduction of sensors and of monitoring and diagnostic functions into station control systems.

PISA for drives

Conventional drives for circuit-breakers, disconnecting switches and earthing switches are still equipped with electromechanical position indicators. These will be replaced in the future by digital optical sensors capable of registering all of the movements of a drive. Records of the total movement of a drive – especially in the case of a breaker – allow a trend analysis to be carried out and the current status of a device to be compared with its original status. In the event of an abnormal movement, an alarm is generated and the record of the curve is shown on the Station Engineering System. In most cases, remedial action will be possible well before a failure could interrupt operation of the substation.

PISA is self-configurable

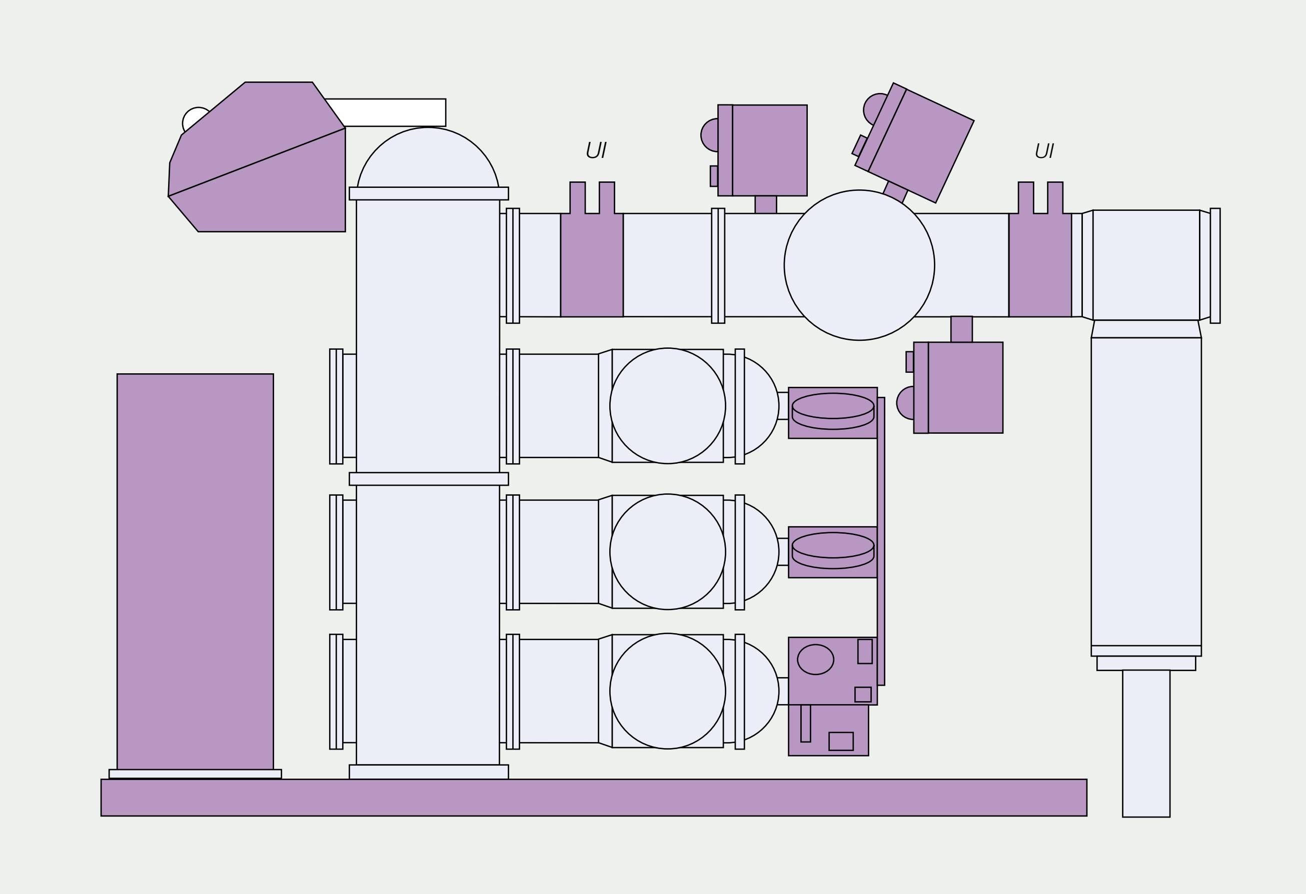
Devices equipped with a PISA interface will announce themselves to the Station Control System and transmit their identity and function without time-consuming local engineering and parameter setting having to be carried out at the process or bay level.

Intelligent switching

Point on wave switching by means of electronic control boxes has started to replace the expensive and unreliable closing and opening resistors. Nowadays, the accuracy of circuit-breaker drives, combined with electronic devices capable of handling fast real-time algorithms, enables point on wave switching to be controlled even in the most complex of cases (eg, with compensated lines) **10**. The effectiveness of controlled switching in terms of overvoltage reduction has been proved by field tests. Alongside synchronized closing, there is a trend towards synchronized opening, ie, opening with an optimum arcing time. With intelligent GIS, the software algorithms that run today on separate, standalone computers will be implemented in the system at the level of the PISA interface for the circuit-breaker.

Maintenance and service

Basically, the GIS maintenance and service procedures are supported by computer-aided monitoring and diagnostic functions. The trend is towards replacement of the regular maintenance work by automatic equipment status checks as well as towards increasing equipment lifetime with the help of device-specific diagnostics running as software modules loaded in the PISA interface. The electronics are fully self-supervised and signal an alarm in the event of a defect. The described redundancy concept enables electronic components to be replaced without having to interrupt operation of the primary device. Sufficient know-how and experience with the self-supervision of electronics in digital equipment already operating in modern substations is available. The principles applied will also be used in the PISA interfaces, although with an



Example of a GIS bay with two UI sensors **11**

improved overall system approach. Control and protection equipment in general is increasingly being built with standardized computer boards. Long-term contracts, standards and the correct selection of electronic components will ensure adequate availability of spare parts during the lifetime of a GIS. Given the rapid pace of development in the electronics sector, electronic components will continue to be replaced on a functional basis.

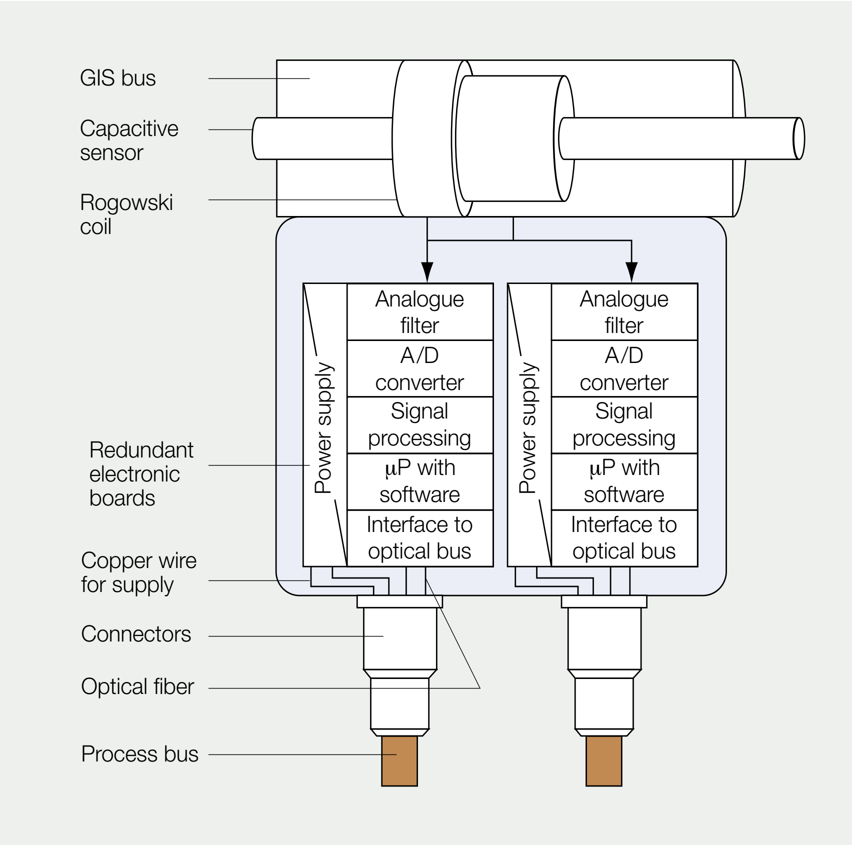
Lifetime of the electronic systems

The lifetime performance of electronic systems has reached a very high level, and know-how based on more than 20 years of experience with such equipment in power generation and transmission is available. It appears that the Mean Time Between Failure (MTBF) of this kind of equipment is much better than originally expected and that further improvements in reliability are likely. Therefore, it can be concluded that intelligent protection and control systems will be much more reliable than the conventional secondary equipment currently in use. In the unlikely event of failure of an electronic component, the faulty device can be replaced immediately, without having to interrupt operation at all.

UI sensor with PISA – the future standard measurement device in GIS

It has been stated that a combined current and voltage sensor is the optimum solution for the measurement of voltages and currents in GIS **11**. The current sensor will be a Rogowski coil and the voltage will be measured by means of a capacitive ring sensor. As already mentioned, the sensor will be equipped with one or, alternatively, where a higher level of redundancy is required, with two separate PISA interfaces and communication buses **12**.

UI sensor with PISA **12**



Schematic diagram of the PISA interface **13**

Nominal ratings

The combined UI sensor will meet the requirements for metering (class 0.1) and protection within the ambient temperature range of −40 to +50˚C. The sensor will therefore replace the conventional current and voltage transformers in the full application range.

Tasks of the PISA interface

The PISA interface is responsible for the analogue filtering, the analogue to digital conversion, the digital filtering and the preprocessing of the measured sensor signals **13**. The output signals of the Rogowski coil and the capacitive voltage sensor are the derivatives of the current and voltage to be measured, and are digitally integrated in the PISA interface. PISA sends the measured signals as serial protocols to the connected control and protection equipment via an optical bus connection (process bus).

Calibration of the sensor and PISA

The primary part of the sensor will be calibrated using a procedure similar to that used with today's conventional transformers, while PISA will be calibrated with the help of a standard reference device. It will be possible to exchange PISA during operation without losing the calibration data of the sensor's primary part.

Communication

The communication between PISA and equipment at the bay level will be established by means of a real-time serial optical bus. A standard similar to that already being used in traction applications will be adopted. This technology is tried and tested, and the communication requirements are similar to those of GIS.

Electromagnetic compatibility (EMC)

The electronic boards of the PISA interface are completely shielded against electromagnetic disturbances. Due to the close proximity to the sensor, very short copper leads which have been properly protected against electromagnetic interference are used between the sensor and the electronics. The small size of the sensor offers very fast transients a much smaller surface area than conventional transformers. Fiber optic links, which are not sensitive to electromagnetic forces, are used for the signal connections to and from the PISA interface on the sensor.

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