



Current measurement systems within the electro-winning industry are a necessity. Traditionally the measurement of dc currents up to 500 kA requires highly sophisticated current transducers. These transducers, commonly based on the Hall effect, tend to be bulky and heavy. In fact those used for high-end currents can weigh as much as 2000 kg!

Though now accurate and reliable, the complexity of these transducers

means that time consuming and rigorous installation and commissioning is required. Care must be taken to minimize potential errors due to asymmetric magnetic fields or cross talk from neighboring currents.

Using optical fiber technology, ABB has developed a sensor, which represents a quantum leap in high dc current measurement. This state-of-the-art fiber-optic current sensor offers outstanding precision and is smaller, lighter and much less complex than traditional transducers and it is about to change the future of high dc current measurement.

A revolution in high dc current measurement

ABB's new fiber-optic current sensor (FOCS) for the electro-winning industry

Klaus Bohnert

Peter Guggenbach

Optical fiber technology has contributed enormously to the increase in the capacity and speed of the world's communication networks. But communication is certainly not its only application. Fiber optics can now be found in a variety of applications, including sensing and measuring.

Because the key components are dielectric in nature and largely immune to electromagnetic interference, fiber-optic sensors are ideal for the measurement of electrical currents and high voltages in electrical power substations, in place of the heavy conventional instrument transformers.

ABB is considered one of the pioneers in the development of this kind of fiber-optic sensors. Over many years, the company has been progressively advancing this technology while working closely with electric power companies in Europe and North America. This interaction has given ABB a thorough insight into the needs of its customers.

The use of fiber-optic current sensors, is not however limited to the electric power industry. In fact, ABB is convinced that optical current sensors will also be of enormous benefit in the electro-winning industry.

In this industry, customers require highly accurate dc current sensors (accuracy to within 0.1%) to control

their processes and operations. The production of aluminum, copper, manganese, zinc, steel and chlorine requires huge amounts of electrical energy. An aluminum potline typically operates at a voltage of 1000 VDC and a current of several hundred thousand amps and to supply this amount of dc power from the ac grid, many rectifiers must be linked together.

ABB is considered one of the pioneers in the development of fiber-optic sensors for the measurement of electrical currents and high voltages in substations.

With optimized processes in place, industries can save energy and monitor actual energy consumption, and therefore control the process more precisely. This is especially important when you consider that a 0.1% measurement error at 500 kA represents a deviation of 0.5 MW, which in turn represents enough power to serve 1000 households with valuable energy!

Hall effect based current transducers

Traditionally, current measurement in the electro-winning industry has been based on the Hall effect¹⁾. A high performance Hall effect dc cur-

rent transducer with magnetic flux nullification **1** has a magnetic core that surrounds a current-carrying bus bar. A number of semiconductor Hall elements, positioned in gaps within the core, are used to detect the magnetic field. The Hall element signals are fed to high gain current amplifiers, whose outputs pass through coils enclosing the magnetic core. These coils generate a magnetic field that compensates the field of the primary current. The sum of the secondary currents is then proportional to the primary current.

This type of transducer, though very accurate, is highly complex and can weigh up to 2000 kg. It also requires sophisticated set-up procedures so that asymmetric field errors and crosstalk from neighboring bus bars are avoided.

It is to overcome these problems and more that ABB developed its new fiber optic current sensor (FOCS).

FOCS versus Hall effect

When compared to a Hall effect dc current transducer, ABB's FOCS is not

Footnote

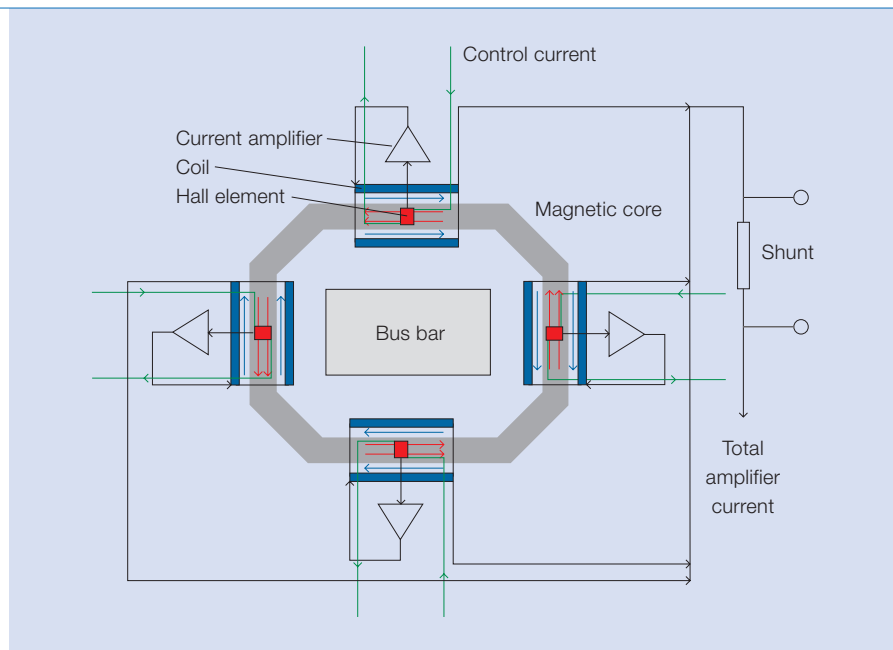
1) Hall effect: In the presence of a magnetic field, positive and negative charges moving through a semiconductor are deflected in opposite directions (Lorentz force). The charge separation gives rise to a (Hall) voltage proportional to the magnetic field.

1 Hall effect dc current transducer

Two conventional Hall effect dc current transducers for 400 kA.



Hall effect current transducer with magnetic flux nullification (principle).



only superior in terms of performance and functionality but it is also smaller and lighter. On top of this, installation and commissioning is very straightforward. In particular, complex field distributions or strong neighboring currents leave the sensor untouched. This gives increased flexibility in the choice of sensor position.

In fact, this type of sensor is ideally suited to meet customer needs for a product:

- Which is installed and commissioned in a matter of hours and not days.
- With a dramatic reduction in complexity.
- That is not affected by complex magnetic field distributions and cross-talk from neighboring bus bars.
- Where accuracy is increased by up to a factor of 10.
- Where the specified accuracy is maintained over a wide temperature range.
- Which provides superior long-term stability.
- With a large bandwidth to enable rapid response to current ripple and transients.
- With the capability of handling both uni- and bidirectional direct currents up to ± 500 kA (plus 20% overcurrent).
- With negligible power consumption.

Fiber-optic current sensor (FOCS)

ABB's new Fiber-optic current sensor (FOCS) **2** for high dc currents is a "spin-off" of a sensor developed for

high-voltage substations. In the electro-winning industry the lateral dimensions of the current-carrying bus bars are much larger when compared to those used in high-voltage substations. This posed some new challenges in the design of an appropriate sensor head.

The sensor makes use of the Faraday effect (See box on page 9). The core components, as shown in **3**, include an optoelectronics module and a single-ended optical sensing fiber that encircles the current conductor [1].

The new fiber-optic current sensor (FOCS) for high dc currents makes use of the Faraday effect.

The optoelectronics module includes a semiconductor light source, a detection circuit and a digital signal processor. Two light waves, with orthogonal linear polarization, travel from the light source, via an interconnecting fiber, to the sensing fiber. A fiber-optic phase retarder converts the linear waves into left and right circularly polarized light waves at the entrance of the sensing fiber.

In the current magnetic field, these light waves travel at different speeds through the sensing fiber, and this in turn creates an optical path difference or, equivalently, an optical phase difference, $\Delta\phi$. The waves are reflected

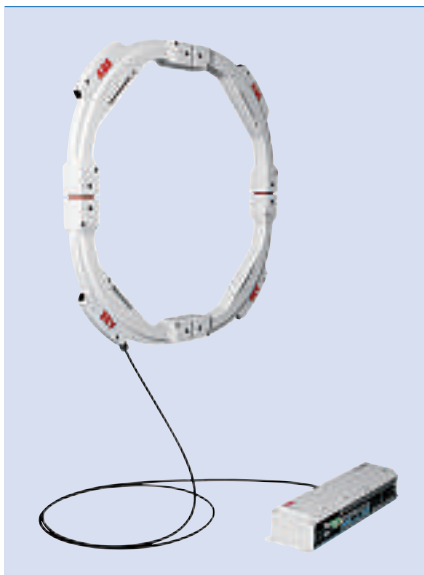
at the end of the fiber and then retrace their optical path back to the optoelectronics module. The two returning light waves are then brought to interference in the detection circuit.

The signal processor converts their optical phase difference into a digital signal.

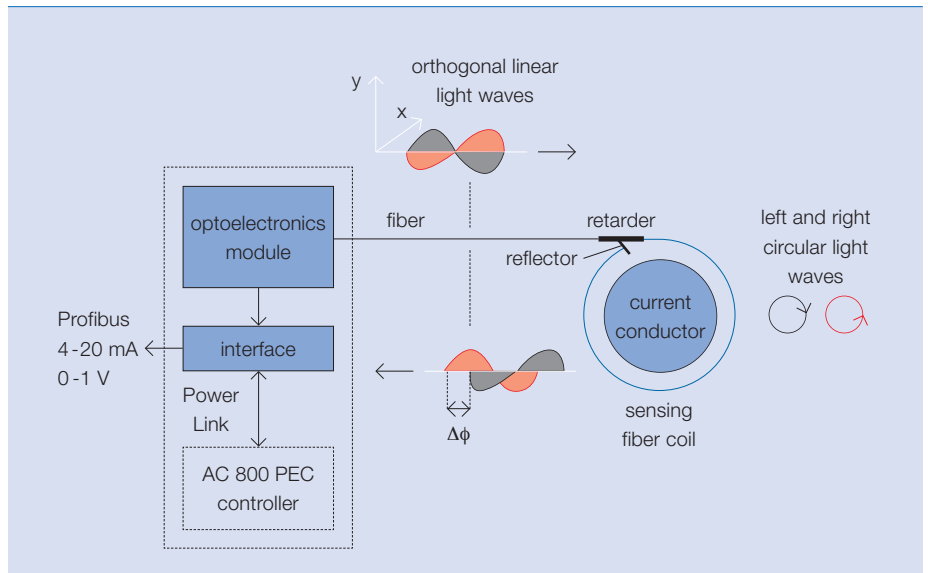
The total roundtrip phase difference is proportional to the line integral of the magnetic field along the closed path described by the sensing fiber and is thus a direct measure of the current. The signal is independent of the particular magnetic field distribution, provided that the number of sensing fiber loops is an integer. (At high currents in the electro-winning industry, a single fiber loop is already sufficient). There is also no cross-sensitivity to currents outside the fiber coil. Neither the diameter nor shape of the fiber loops has any influence.

The roundtrip time difference between the left and right circular light waves is between 10^{-21} and 10^{-15} seconds depending on the current. Direct measurement is not feasible and therefore the path or phase difference – which corresponds to a fraction of the optical wavelength (820 nm) – is measured with extremely high precision instead. To do this, the waves are brought to interference, ie, they are superimposed on each other. Depending on their relative delay the waves interfere constructively or destructively.

2 ABB's new fiber-optic current sensor.



3 Schematic illustration of ABB's fiber-optic sensor for high dc currents.



ly. The smallest path difference that can be measured is 100 times smaller than the diameter of a hydrogen atom and corresponds to a current of 0.25A (for one fiber loop and a measurement time of one second). Presently, the largest measurable current, corresponding to a path difference of a full wavelength, is ± 600 kA (± 500 kA + 20% overcurrent).

One of the advantages of operating the sensing coil in reflection mode is that the sensor output becomes immune to mechanical shock and vibration. In reflection mode, the polarization states of the light waves swap at the coil end. As a result, the reciprocal vibration-induced phase shifts cancel each other and the non-reciprocal

magneto-optic phase shifts double during the round trip.

Sensing head

The stress-free packaging of the sensing fiber is absolutely crucial when it comes to the accuracy of a fiber-optic current sensor. Any form of stress will disturb the circular light waves and in turn the recovered magneto-optic phase shift. Even stress caused by common protective fiber coating shrinkage at low temperatures is not acceptable.

ABB therefore developed a proprietary technique of packaging the sensing fiber in a flexible “sensing strip” ⁴. This method provides excellent accuracy (within 0.1%) over a

temperature range from -40°C to 85°C and its flexible form facilitates transport and installation. The temperature dependence of the Faraday effect (0.7% change over 100°C) is inherently cancelled by an opposite contribution from the retarder.

As a further benefit, sensor calibration performed in the factory is not affected by shipping and handling; thereby

The sensing fiber is packaged in a flexible “sensing strip” which facilitates transport and installation as well as excellent accuracy over a wide temperature range.

eliminating the need for any on site recalibration after the sensor has been installed.

The sensing strip containing the sensing fiber is accommodated in a modular sensor head housing which consists of individual segments of fiber reinforced epoxy. This housing can be easily adapted to different bus bar cross sections by adapting the lengths of the straight segments, ⁵, and the sensor can be installed without opening the current-carrying bus bars ⁶.

Optoelectronics module

The technology of the optoelectronics module is the same as that found in fiber gyroscopes. Optical gyroscopes have replaced their mechanical counterparts in many high performance navigations systems, and they have well and truly proven their ability in demanding applications in the air, on land and at sea.

The built-in digital signal processor provides high accuracy and excellent long-term stability. In addition, the closed-loop detection circuit nulls the current-induced optical phase shift and thus produces a perfectly linear output over the full dynamic range.

The optoelectronics module is integrated into ABB's AC 800PEC power electronics controller ⁷, which can be placed up to 70 m away from the sensing head. The sensor can be delivered as part of the ABB power converter system and is also available as a stand-alone device. The optoelec-

The Faraday effect

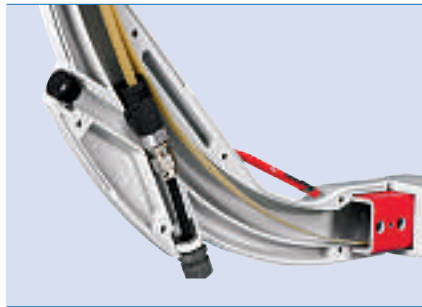
The optical current measurement is commonly based on the Faraday effect, named so after the English scientist Michael Faraday (1791–1867). The Faraday or magneto-optic effect is the phenomenon that the plane of polarization of a linearly polarized light wave traveling through a medium, for example a piece of glass, is rotated in the presence of a magnetic field. Linear light can also be represented by a pair of co-propagating left and right circularly polarized light waves. In a magnetic field the two circular waves travel with different speeds and thus accumulate a phase difference, which causes the rotation, by an angle ϕ_F , of the resultant linear wave. In a current sensor, the light travels along a closed path defined by the fiber around the conductor. In reflection mode the phase difference is given by:

$$\Delta\phi_F = 4VN \oint \vec{H} ds = 4VN I$$

- V is the Verdet constant, a material dependent measure for the magnitude of the Faraday effect.
- N is the number of turns of light around the conductor.
- I is the current.

As a result of the closed path, the signal depends only on the current and the number of fiber loops, and not on dimensional parameters such as the diameter or the fiber loop shape.

- ⁴ A segment of the sensor head housing. The sensing fiber is embedded in a flexible and robust sensing strip.



- ⁵ The modular sensor head housing can be easily adapted to various conductor cross-sections.



6 Sensor head housing mounted around current carrying bus bars.



tronics module outputs a digital signal with 24-bit resolution via a synchronous interface. This digital signal is sent to the AC 800PEC controller via ABB's high-speed optical PowerLINK protocol.

For stand-alone applications, a digital signal is also available over the PROFIBUS DP SLAVE fieldbus protocol. Furthermore, 0(4) to 20mA and 0(0.2) to 1V analog output signals are provided. Digital signal processing, like data history logging or harmonic analysis, is provided at a customer's request. The functional integrity of the device is monitored by built-in self-test features and then reported to the host controller.

The many innovations comprised by ABB's FOCS have led to about a dozen pending or already granted patents.

Customer benefits and product specifications

Compared with conventional Hall effect based direct current transducers, the fiber-optic current sensor offers a variety of benefits for users including the following:

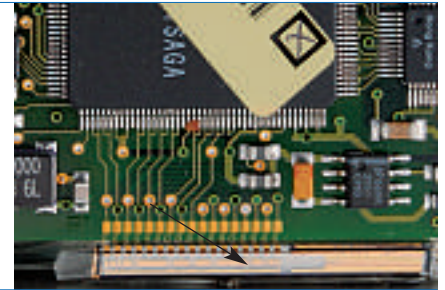
- *The sensor is significantly easier and faster to install.*
- *No special effort is required to magnetically center the head.* This gives the customer outstanding flexibility when it comes to sensor placement.
- *Very few restrictions exist on where to place the measuring heads.* The ease with which the sensor can be installed means that an existing plant measuring system can be quickly replaced.
- In contrast to conventional current transducers, *errors due to asymmet-*

7 AC 800 PEC power converter controller

a) ABB's AC 800 PEC power converter controller hosts the optoelectronics module of the sensor. This module, based on fiber gyroscope technology, detects the magneto-optic phase shifts.



b) An integrated optic lithium niobate phase modulator (arrow) is a key component of the detection circuit.



ric field distribution and magnetic overload are inherently eliminated.

- *Sensor head complexity has been dramatically reduced.* This in turn reduces the probability of failures.
- *The sensor is able to handle bi-directional magnetic fields.* A local reversal in the field direction, caused by strong neighbouring currents, does not result in an inaccurate sensor output. Furthermore, the sensor indicates when reversed currents occur.
- The *large bandwidth* (4 kHz data sampling rate) enables the recovery of ac current components such as ripple and fast transients and it permits very short reaction times for process control as well as harmonic analysis. Consequently the sensor will open up new data acquisition capabilities for high dc current process lines.
- *The sensor head is all dielectric and therefore very safe.* The signal processing electronics is fully galvanically isolated from the bus bars.
- *Power consumption of the optical sensor is negligible* compared with conventional sensors, which consume up to several kilowatts of power.

Key specifications are:

- The sensor is capable of handling both uni- and bidirectional currents up to ± 500 kA (plus 100kA over current).
- The sensor is accurate to within $\pm 0.1\%$ from 1 to 120% of full scale current.
- The data-sampling rate is 4 kHz.
- The operating temperature range for the sensor head is -40 to 85°C , and -20 to 55°C for the controller

electronics (0 to 65°C with a PROFIBUS module).

Further applications

ABB's target markets for fiber-optic current sensors include metering, and control and protection in high voltage substations. Because of its drastically reduced size and weight, the sensor can be easily integrated into existing equipment, such as circuit breakers or bushings, thus saving space and installation costs.

The sensor is also of interest for high-voltage direct current (HVDC) systems that are used to transmit electric power over long distances. Railways are another promising area of application. In fact, ABB has already installed a few dozen sensors, based on a prototype version, in substation protection systems belonging to the Italian railways.

ABB's new FOCS is truly a quantum leap in current measurement.

Klaus Bohnert

ABB Switzerland Ltd., Corporate Research
klaus.bohnert@ch.abb.com

Peter Guggenbach

ABB Switzerland Ltd., High Power Rectifiers
peter.guggenbach@ch.abb.com

References

- [1] K. Bohnert, G. Gabus, J. Nehring, H. Brändle: "Temperature and vibration insensitive fiber-optic current sensor". Journal of Lightwave Technology 20 (2002) 2, 267-276.