





# Light measures current

A fiber-optic current sensor integrated into a high-voltage circuit breaker

KLAUS BOHNERT, RICHARD THOMAS, MICHAEL MENDIK – Current and voltage measurements are two key functions in the control and protection of electric power grids. Traditionally, they have been performed using so-called instrument transformers – somewhat bulky and heavy devices that can weigh up to several tons. It has long been recognized that fiber-optic-based devices that exploit the Faraday effect have great potential as an attractive new technology for current measurement. The remarkable progress made in optical telecommunications over the last 20 years has delivered components such as light sources, optical fibers, modulators and photodetectors that can be reused to produce fiber-optic current sensors (FOCSs) that are reliable and commercially attractive. Moreover, FOCSs have also benefited from the rapid development in recent years of fiber-optic gyroscopes, which use techniques that exploit the same basic physical effects.

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#### Title picture

For many decades, current measurement in high-voltage equipment has relied on bulky transformers that could weigh up to several tons. These will now be replaced by ABB's fiber-optic current sensor, whose small size allows it to be integrated into primary equipment such as circuit breakers.

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Presently, currents in high-voltage equipment are measured using bulky and heavy current transformers (CTs). These use the principle of electromagnetic induction to generate a small secondary current, typically 1 A or 5 A at rated current, from a primary current, which then serves as an input for protection relays or energy meters. Such transformers have represented the state of the art for many decades and they operate reliably under the harsh conditions found in an outdoor substation. However, besides their size and weight, they have a number of additional shortcomings – the most important of which is that, as a result of magnetic saturation and limited bandwidth, the waveform of the secondary current is often not a true image of the primary current.

Over 40 years ago it was recognized that the Faraday effect in optical fibers could be the basis of a new, and better, technology for current measurement. But it is only in the last 20 years that appropriate technology has become sufficiently mature to allow it to be used as a commercially attractive basis for FOCS applications. The remarkable progress made by the optical communications business has provided many components that can be reused for the FOCS – such as light sources, fiber-optics, modulators and photodetectors.

FOCS has also benefited from the development of fiber-optic gyroscopes. Today, fiber gyros are in use in numerous navigation systems – in the aerospace industry, for example. These gyros use techniques similar to those employed by the FOCS to measure the differential phase shift of light waves. Whereas in gyroscopes the phase shift is the result of a rotation (the Sagnac effect), in optical current sensors it is caused by the magnetic field of the current to be measured.

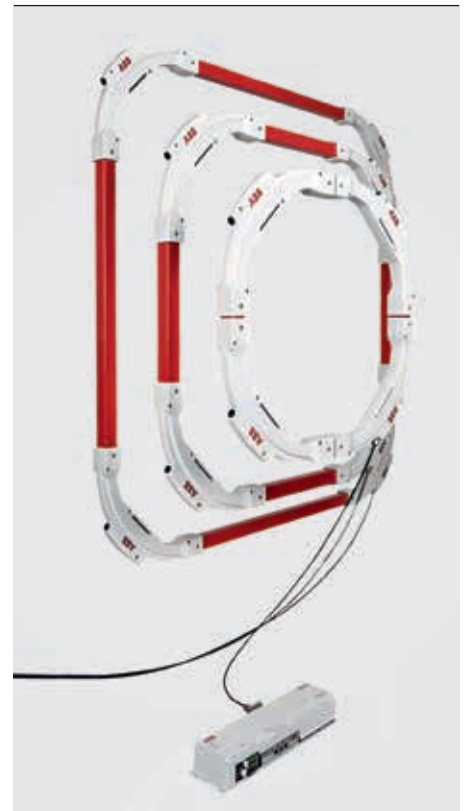
#### FOCS history

In 2005, ABB introduced a high-performance fiber-optic current sensor for the measurement of DC up to 600 kA, particularly for use in the electro-winning of metals [1,2] → 1. The sensor accuracy is within 0.1 percent over a range from 1 percent to 120 percent of the rated current and in temperatures from –40 to +80 °C. The sensor is now in use worldwide – in aluminum smelters, copper electro-winning facilities, chlorine plants and even nuclear fusion research installations.

Recently, ABB has developed the sensor further with a view to implementing it in high-voltage substations. Because of its small size and flexible form factor, an optical current sensor does not need to be a standalone device like a traditional instrument transformer. Instead, it can be integrated into primary high-voltage equipment such as circuit breakers – this results in substantial savings in space and installation costs. Another important aspect of the new technology is its ability to communicate digitally, via an optical process bus, with control and protection devices. The process bus replaces large numbers of copper cables and provides

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#### 1 Fiber-optic current sensor for large DC values

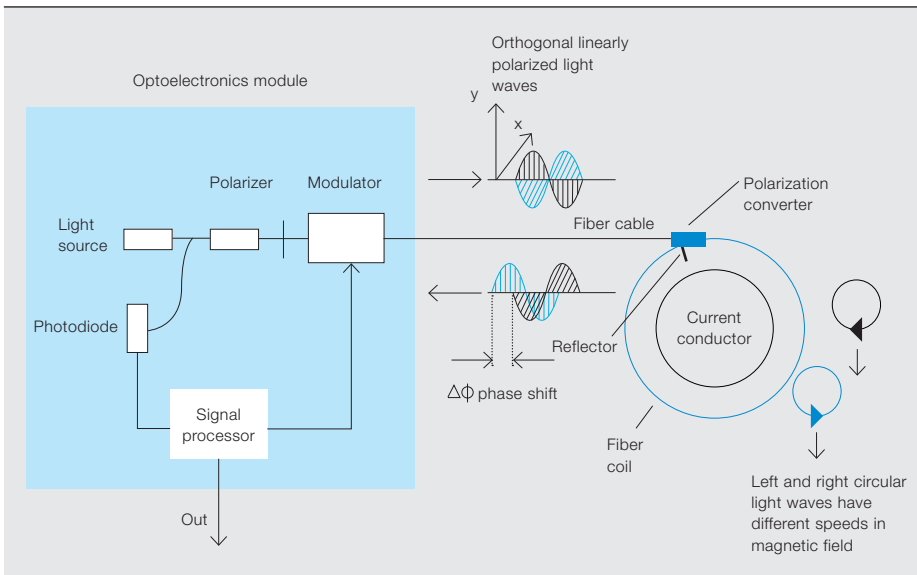


more flexibility in the configuration of a substation.

#### How it works

The FOCS exploits the Faraday effect. The Faraday effect is caused by the fact that left and right circularly polarized waves propagate at slightly different speeds when they travel in a medium that is subject to a magnetic field. To exploit the effect, a linearly polarized wave is decomposed into two such circularly polarized components that are then coupled into an optical fiber that is exposed to a magnetic field (caused, in the case discussed here, by the current to be measured). The effect of the relative phase shift between the two components caused by the Faraday-effect-induced speed difference is to rotate the orientation of the wave's linear polarization. This can be used to deduce the magnitude of the current.

The main components of the FOCS are an optoelectronics (OE) module at ground potential and a coil of sensing fiber, which is wound around the current conductor → 2. The OE module includes a semiconductor light source and a closed-loop detection circuit with a fiber-optic polarizer, an optical phase modulator and a digital signal processor. The module sends two



light waves with orthogonal linear polarization to the sensing fiber coil. At the coil entrance a fiber-optic polarization converter transforms the linear waves into left and right circularly polarized light waves. These waves travel at different speeds through the sensing fiber in the magnetic field (caused by the current) as a result of the Faraday effect, as explained above, and this in turn creates an optical phase difference. The waves are reflected at the end of the fiber and they retrace their optical path back to the optoelectronics module where they interfere at the polarizer. The signal that results from the interference depends on the phase difference and is measured by a photodiode. The closed-loop control circuit reverses the current-induced phase shift by means of a phase modulator so that the phase difference of the waves when they interfere at the polarizer is always kept at zero. The feedback signal to the modulator is then essentially an image of the primary current and the digital sensor output is derived from this signal. A particular advantage of this closed-loop detection scheme is that the signal is perfectly in proportion to the primary current over the entire measurement range.

The roundtrip phase difference of the two light waves is proportional to the number of fiber loops and the line integral of the magnetic field along the closed path described by the sensing fiber. Geometrical parameters such as the coil diameter or the position of the conductor inside the fiber coil do not affect the signal. Currents outside the coil have no influence.

Operation of the sensing fiber in reflection mode has the advantage that the sensor becomes immune to mechanical disturbances. The mirrored coil end swaps the polarization states of the light waves. As a result, vibration-induced phase shifts cancel each other out over one roundtrip of the waves while the non-reciprocal magneto-optic phase shifts double. The basic concept of the sensor was invented at ABB in 1992 and has been adopted by others.

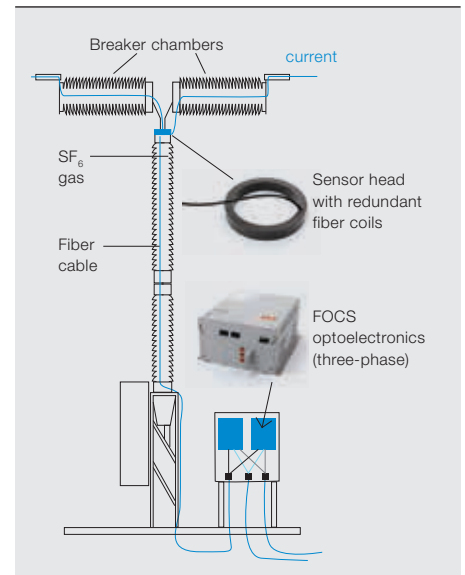
By appropriately selecting the number of fiber loops, the measurement range can be optimized for specific applications. The sensor described here has a range of  $\pm 180$  kA. The operating temperature range of the sensor head is from below  $-40^\circ\text{C}$  to  $105^\circ\text{C}$ . The OE module is designed for operation in a heated outdoor cubicle. It can be operated with three fiber coils to cover all three phases normally found in a high-voltage installation.

**FOCS benefits**

Particular benefits of the FOCS are:

**High accuracy**

Within the bandwidth determined by the output data rate, the sensor delivers a true image of the primary current waveform that is not affected by magnetic saturation or remanence. The DC contents of a current are correctly recorded. The sensor targets both protection and metering applications.



The remarkable progress made by the optical communications business has provided many components that can be reused for the FOCS, such as light sources, fiber-optics, modulators and photodetectors.



## FOCS has also benefited from the development of fiber-optic gyroscopes.

### Reduced environmental impact

The FOCS saves the aluminum, copper, insulation materials and transformer oil that constitute a corresponding conventional CT. A 550kV CT, for example, can have a weight of about 3.5 tons, which may include 500kg of oil.

### Zero footprint capability

The sensor need not be a standalone device but may be integrated into other power products such as circuit breakers or bushings → 3.

### Safety of operation

Risks of catastrophic failure, eg, during earthquakes, or safety issues due to an open secondary circuit, are excluded. The electronics are galvanically separated from high voltages.

### Digital communication

A fiber-optic IEC 61850-9-2LE process bus connects the FOCS to bay-level control and protection devices and replaces large amounts of copper cable – as much as tens of kilometers per substation. It also

provides more flexibility in the configuration or later reconfiguration of a substation. The communication data rate is 4 or 4.8kHz at line frequencies of 50 or 60Hz, respectively. Higher data rates (eg, up to 100kHz), that may be of interest in other applications are possible with alternative interface options.

### FOCS in live tank breakers

The small and easily adaptable size of a current sensor fiber coil makes it possible to integrate the sensor into other power products. For example, a redundant three-phase FOCS system can be integrated into an ABB double-chamber circuit breaker such as the 550kV HPL550B2 → 3 – 4. Each of the three ring-shaped sensor head housings shown in the figure contains two fiber coils and is mounted at the upper end of the corresponding breaker pole. The current path is modified in such a way that the current flows through the coils as indicated. The two fiber-leads to the coils are in a special protective cable that is suited for the live tank breaker (LTB) gas atmosphere. The cable runs to ground through the gas volume and leaves the breaker pole through a gastight feedthrough. The two three-phase OE modules are mounted in a cubicle near the breaker or are attached to the breaker support frame. Redundant IEC 61850-9-2LE links connect the sensors to protection relays such as ABB's REL670 in the control housing → 5. The solution has many benefits:

- In-factory installation: The integration of the sensor heads into the LTB and the OE modules into their cubicle is done in the factory. The only remaining

installation work to be done in the field is to set up the cubicle for the OE modules and deploy the fiber cables.

- The sensor head is part of the LTB pole and does not interfere with the LTB assembly in the field. In fact, only minor changes in the LTB assembly procedures are needed.
- There is no need for an extra insulator to bring the fiber from high voltage to ground.
- Zero footprint: The space required for a conventional CT or standalone optical CT is eliminated. This reduces the substation size and saves real-estate costs, particularly when the sensors are combined with disconnecting circuit breakers [3].
- The CT foundation and support structures are no longer needed.
- The outdoor placement of the optoelectronics modules near the LTB minimizes the length of sensor fiber cable required.
- The transmission of digital optical signals from the sensor electronics to the substation control function via the redundant IEC 61850-9-2LE links is immune to disturbance.

The design of the LTB with an integrated FOCS was verified to be in compliance with the relevant type tests as defined by IEC standards. The tests included high-voltage tests, T100 tests (ie, verification of breaker operation at high current and voltage), temperature-rise tests (temperature rise at a current of 4,000 A<sub>rms</sub>) as well as mechanical endurance tests consisting of over 10,000 breaker open-and-close operations. Proper sensor operation be-



fore, during and after the tests was verified. Other tests ascertained the electromagnetic immunity of the sensor.

#### Ascertaining reliability

The FOCS technology has already been proven in the harsh environments of the electrowinning industry over a period of several years. However, the demands on reliability in high-voltage substations are even more stringent – for example, no particular maintenance or recalibration should be necessary during a lifetime in the field. Therefore, the reliability of the FOCS and its components is being verified by accelerated aging and long-term performance tests in-house. Self-diagnostic functions continuously monitor the operation of the sensor. Furthermore, precommercial field installations serve to gather experience of installation and commissioning of the new technology and to prove its reliability under substation conditions.

#### Technology pilot

A FOCS pilot installation has been set up in collaboration with Svenska Kraftnät (Swedish National Grid) at a 420 kV substation → 6–7. The installation consists of a three-phase LTB with a redundant three-phase FOCS system. The two OE units are mounted in the phase B breaker drive cubicle. Two IEC 61850-9-2 links connect the OE units to two ABB REL670 digital relays in the control housing. A CT with protection and metering cores serves as a reference. A pulse-per-second source synchronizes the system. Data is recorded at regular intervals for long-term comparison. Furthermore, the protection function can request disturbance recordings to be

made. Besides verifying the performance and reliability of the sensor under field conditions, the pilot has also served to verify the assembly procedures in the factory, and the installation and commissioning in the field.

The system has been in incident-free operation since April 2010. Performance has been within specifications. Moreover, the superiority of a FOCS over a conventional CT in the recording of transient fault currents has become obvious. This may lead to the development of more efficient protection and control functions in the future.

#### Looking ahead

The FOCS technology will serve as a platform for other high-voltage applications. The variable diameter of the sensing head allows the sensor to be easily adapted to high-voltage equipment such as gas-insulated switchgear (GIS) or generator circuit breakers. By choosing the fiber loop number appropriately, high accuracy can also be achieved at low currents, eg, in zero sequence current measurements. New or improved substation protection and monitoring functions may follow from the fast response of the FOCS and its precise measurement of both AC and transient DC.



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