Technology leap in DC current measurement opens new opportunities for aluminium smelters

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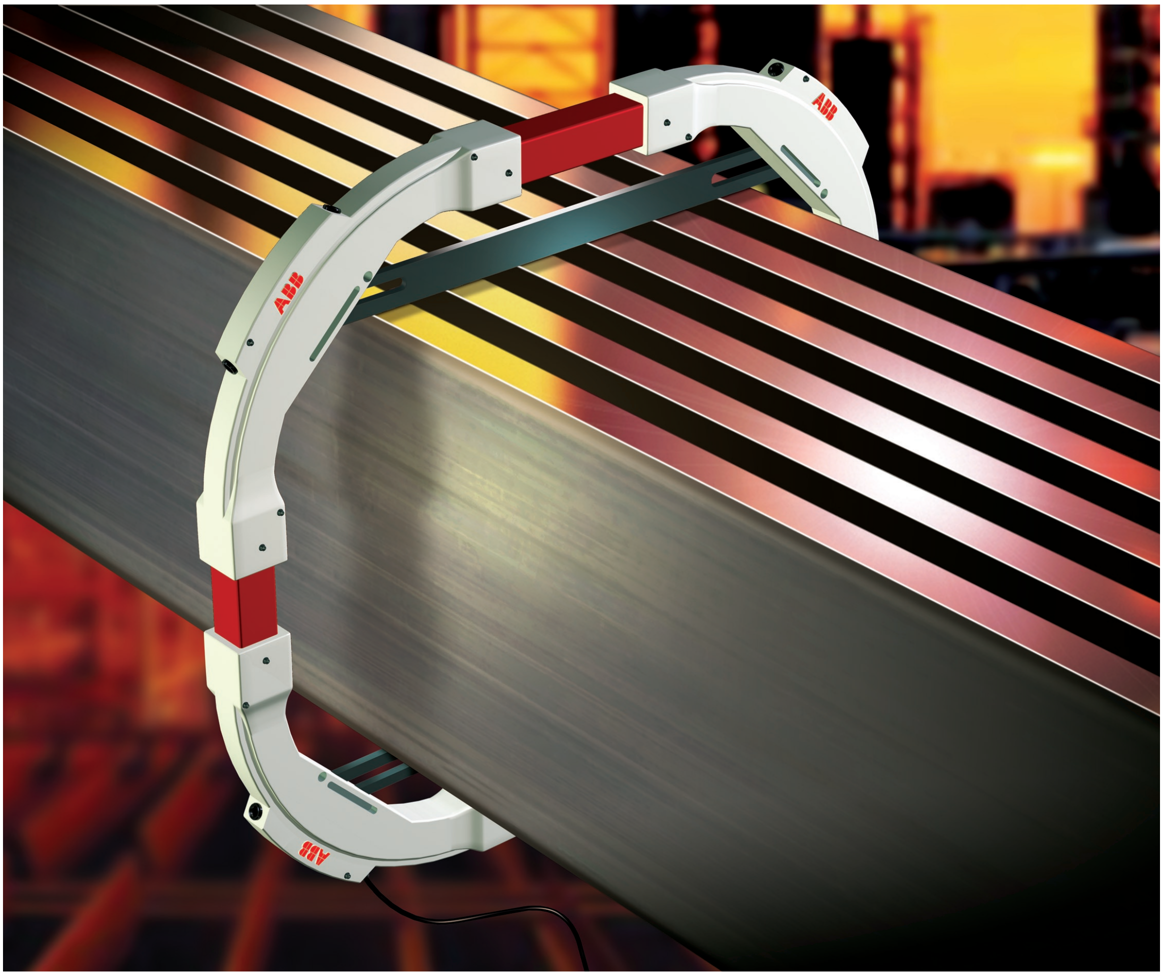

Technology leap in DC current measurement opens new opportunities for aluminium smelters

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Within the electro-chemical industry, dc current measurement systems are required and well-established for process control and regulation. Conventional high dc current transducers utilize the Hall effect to measure the magnetic field around the current carrying bus bars. Over the years Hall effect transducers have become very accurate and reliable. However, they are rather complex systems and demand intricate installation and commissioning procedures. Special care must be taken to avoid erroneous output due to asymmetric field distributions and to disturbances from neighbour currents or busbar corners. ABB's newly developed Fiber-Optic Current Sensor (FOCS) is a spin-off from a sensor developed for high-voltage substations and it opens totally new opportunities in the field of high current dc measurement.

Conventional Hall effect current transducers

A Hall effect dc current transducer (figs. 1 and 2) has a magnetic core surrounding the current-carrying bus bars. A number of Hall elements are positioned in gaps along the core and detect the magnetic flux. In the most accurate models, the signals of the Hall elements are fed to high gain current amplifiers. These amplified currents pass through solenoids around the core and generate a magnetic field compensating the field of the primary current. The sum of the solenoid currents is proportional to the primary current. Simpler types of Hall current transducers, commonly with lower accuracy, work without closed-loop flux compensation and translate the Hall currents directly into an output signal.

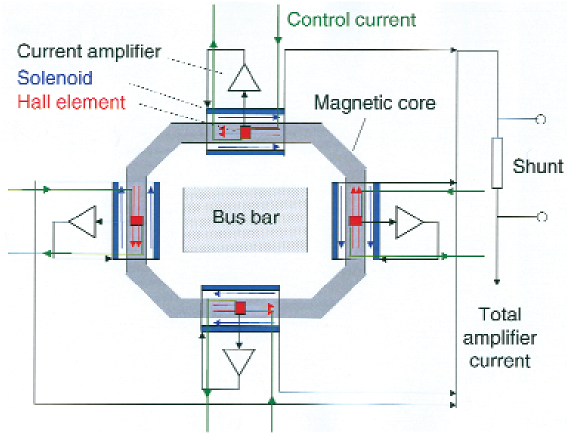

Fig. 1: Hall effect dc current transducer with magnetic flux nullification (principle)

Hall effect dc current transducers with closed-loop magnetic flux nullification, though very precise, are rather complex systems, with weights up to 2 000 kg. Furthermore, in the case of angled bus bar arrangements, an analysis of the magnetic field distribution is often necessary in order to place the transducer head in such a way as to minimise errors due to asymmetric fields, or cross-talk from neighbour currents. For example, erroneous output may result from inhomogeneous heat dissipation in the transducer, or from amplifier saturation at local field maxima, or from a local reversal in the field direction caused by neighbour currents. These are only a few of the aspects where fiber-optic current sensors offer clear advantages.

Fig. 2: Hall effect dc current transformers LEM LKP 400

Fiber-Optic Current Sensor (FOCS)

In the fiber-optic current sensor a simple loop of optical fiber around the bus bar replaces the sophisticated head of the conventional transducer. The sensor perfectly integrates the magnetic field along the closed path described by the sensing fiber. As a result, the signal is independent of the detailed form of magnetic field distribution and is only determined by the enclosed current. All currents outside the fiber loop are of no influence. Sensor placement is therefore uncritical. The simplicity of the system reduces to a few hours the time required for installation and commissioning.

The sensor makes use of the Faraday effect in the fiber. The Faraday effect is the phenomenon that in a medium such as glass right and left circularly polarized light waves travel at different speeds if a magnetic field is applied along the propagation direction (fig. 3). As a result the waves accumulate a path difference δL or equivalently a phase difference $\delta\Phi_F = 2$ V L H. Here, V is a material constant (Verdet constant), L the length of the rod, and H the magnetic field. Fig. 4 schematically illustrates the set-up of ABB's fiber-optic current sensor. Two light waves with orthogonal linear polarizations travel from the optoelectronics module, which includes a semiconductor light source, via an interconnecting fiber to the single-ended sensing fiber. The sensing fiber forms an integral number of loops, N, around the bus bar. A single loop is commonly sufficient for high dc currents. At the entrance of the sensing fiber a fiber-optic phase retarder converts the orthogonal linear waves into left and right circularly polarized light. The circular waves travel through the coil of sensing fiber, are reflected at the end of the fiber and then retrace their optical path back to the coil entrance. Here, they are again converted into orthogonal linearly polarized waves. Due to the reflection the polarization directions of the returning waves are swapped with respect to the initial forward propagating waves. Since the two circularly polarised waves travel at slightly different speeds through the sensing fiber if a dc current, I, is flowing, the two returning light waves accumulate a phase difference given by $\Delta\Phi_F = 4$ V N I. The phase difference is proportional to the line integral of the magnetic field along the sensing fiber and is therefore a direct measure for the current. The returning waves are brought to interference in the optoelectronics module. The signal processor then converts the optical phase difference into a digital signal. Besides the simplicity of the arrangement, a particular advantage of operating the sensing coil in reflection is the fact that the sensor signal is largely immune to mechanical perturbations such as shock and vibration. While the non-reciprocal Faraday optical phase shifts double on the ways forward and backward, phase shifts caused by mechanical disturbances are reciprocal and cancel each other.

The technology of the optoelectronic detection circuit is the same as is used in fiber gyroscopes and it has been well proven in demanding navigation systems. Fiber gyroscopes use the Sagnac effect seen by two counter-propagating light waves in a fiber coil to measure rotation velocities.

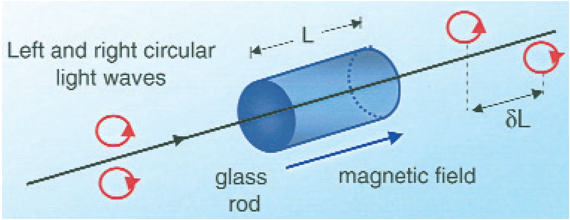

Fig. 3: Faraday effect

ABB FOCS system design and interfaces

The sensing fiber is packaged in proprietary sensing strip, which allows perfectly closing the fiber loop in a straightforward manner. The sensing strip also prevents any uncontrolled mechanical stress on the sensing fiber. This is important in order to maintain high accuracy and stability. On-site recalibration after installation of the sensor is not necessary. The sensing strip resides in a modular and lightweight housing consisting of segments of fiber re-enforced epoxy (fig. 5). The sensor head can be installed without opening the bus bars. By varying the lengths of the straight segments the head can be easily adapted to different bus bar cross-sections. The sensor head is connected to the optoelectronics module via a robust fiber cable.

The optoelectronics module of the sensor is integrated into ABB's AC 800PEC Power Electronics

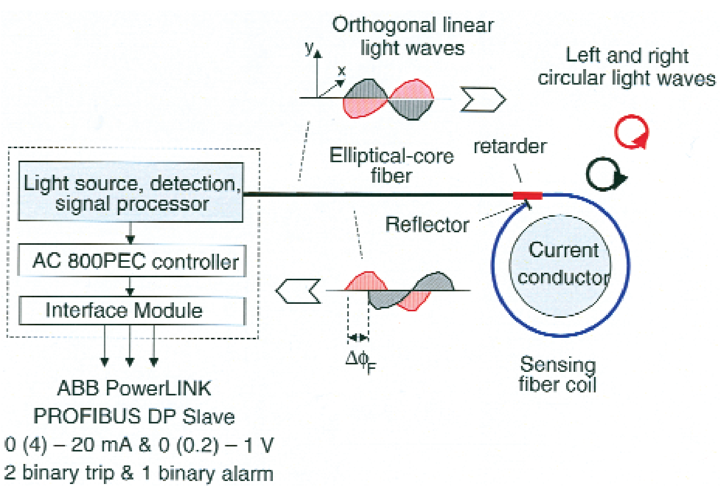

Fig. 4: Fiber-optic current sensor

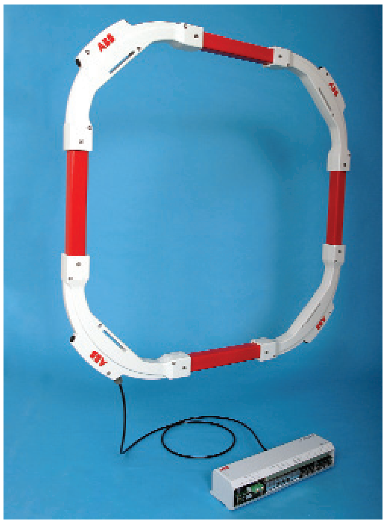

Fig. 5: The ABB FOCS sensor head housing is modular and lightweight

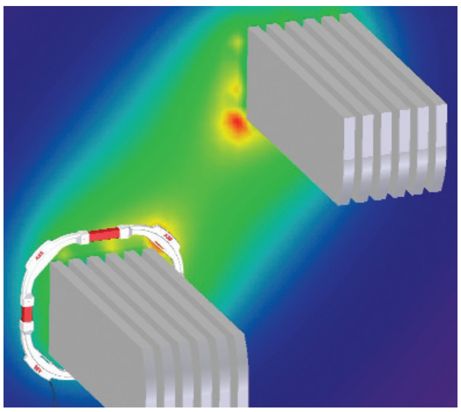

Fig. 6: The ABB FOCS maintains high accuracy even in strongly inhomogeneous magnetic fields

Controller (fig. 4). The sensor is available as part of the ABB high power converter systems as well as a stand-alone device. Build-in self-test features monitor the functional integrity of the controller and the sensor. Three different output signal formats are available: a digital output with 24 bit resolution via ABB's high-speed optical PowerLink protocol, via the Profibus DP Slave fieldbus protocol as well as analog current and voltage outputs (0 (4) -20 mA and 0 (0.2) -1 V). Additionally, the three following independent change-over contacts are provided to allow for monitoring and signalization.

- Instantaneous DC Over Current Trip or inverse Current Trip (fig. 7),
- Instantaneous Reverse Current Trip,
- General Alarm in case of over-temperature or other failures.

FOCS performance and specifications

The sensor is available for rated currents up to 500 kA with corresponding sensor head sizes. The current measuring range covers several orders of magnitude with very good accuracy, also far below the specified nominal current. The accuracy is within ±0.1% from 1% to 120% of the nominal current. The temperature range of operation is -40°C to 80°C for the sensor head and –25°C to 65°C for the electronics (0°C to 65°C with a Profibus module). The data sampling rate is 4 kHz and allows recovery of ac current components up to 2 kHz. Fig. 8 shows the signal vs current relationship for a sensor with a rated current of 260 kA over a range from 3 kA to 300 kA (black squares). The deviation of the signal from linearity (blue squares) is well below 0.1%. Fig. 9 shows the signal at constant current (about 7.7 kA) over a 24 h period. The signal stability is again well within 0.1%.

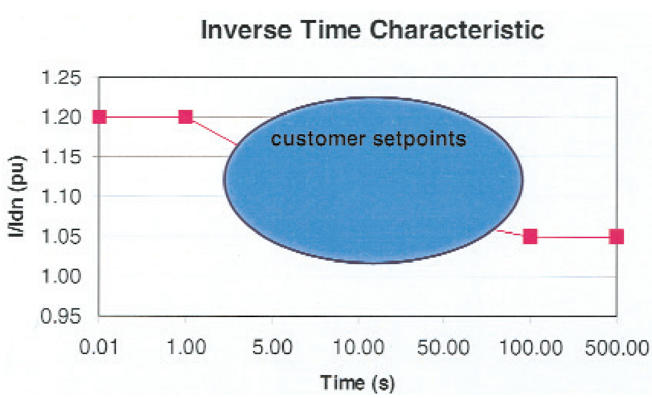

Fig. 7: The ABB FOCS inverse time over current characteristic (five set-points can be specified by the customer, where I/Idn defines the current limit Idn per unit and time defines the maximum duration time of this current limit before tripping)

Comparison of Hall effect and fiber-optic DC current transducers

Hall effect and optical current transducers are both highly accurate. However, the optical sensor offers a number of important advantages (see also table 1):

- The high accuracy of the optical sensor is maintained over a very wide operating range of currents.
- The perfect line integration of the magnetic field eliminates erroneous output in case of angled conductor arrangements, inhomogeneous magnetic fields, and strong neighbour currents (see illustration in fig. 6).
- The sensor is able to handle bi-directional currents and magnetic fields. A local reversal in the field direction, caused by high neighbour currents, does not lead to errors.
- Local field enhancements will not cause saturation.
- The good field integration results in more flexibility in the choice of the sensor placement. Even a small space on the busbar is sufficient to install the sensor.
- The large bandwidth enables the detection of current ripple and recording of transients.
- The complexity of the sensor head and thus the risk of faults is significantly reduced.
- The sensor electronics are electrically isolated from the sensor head.
- Both digital and analog outputs are available to perfectly fit into today's de-centralized industrial automation technologies.

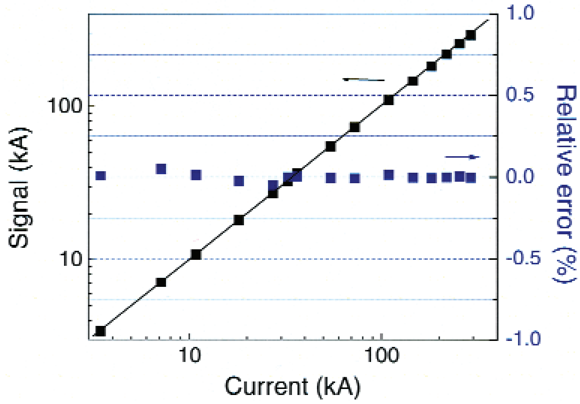

Fig. 8: Signal vs. current (black) and relative error (blue) for a sensor with 260 kA rated current

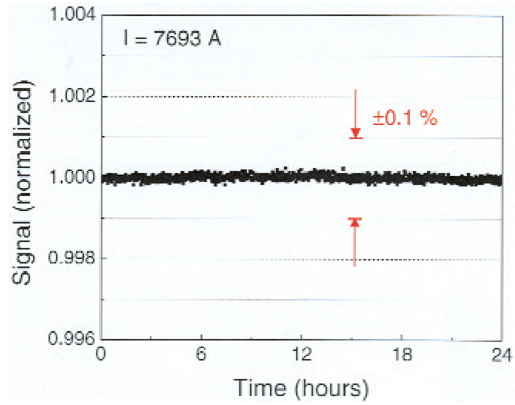

Fig. 9: Signal vs. time at a constant current of 7693 A

- The digital signal processing ensures good long-term stability, enables digital communication and data acquisition.
- Power consumption of the optical sensor is negligible, whereas flux-compensated Hall effect transducers consume up to several kilowatts.

These advantages lead to following customer benefits:

- No special building structures are needed to install the ABB FOCS Fiber-Optic Current Sensor.
- The magnetic centering of the sensor is not critical.
- Busduct studies are not required to find the optimal placement of the sensor. It can be installed almost anywhere.
- The sensor installation is straightforward and can be completed in a few hours instead of several days.
- No proprietary protocol. Any control system can be used which can connect to a Profibus DP Slave fieldbus protocol, others on request.
- The customer's digital regulation system can make use of the full FOCS accuracy, without any additional signal transducers, throughout the complete communication and measuring chain.
- The sampling rate of 4 kHz leads to a short dead time and permits very short reaction times, which can be quite crucial in some applications.
- With high accuracy over the full operating range, exact control and regulation of the process can be assured, even when operating below or above the rated current.
- Instantaneous dc over current or inverse time current trip signals can be provided (fig.7).
- The ability to handle bidirectional currents enables the current sensor to indicate when reverse currents occur and to provide a trip signal.

Attribute	Hall effect	Optical
Accuracy	☺	☺
Dynamic range	☺	☺
Bandwidth, recording of transients	😐	☺
Complexity	☹	☺
Application flexibility	☹	☺
Weight	☹	☺
Transport and installation	☹	☺
Magnetic centering	☹	☺
Low current detection	☹	☺
Bidirectional currents	😐	☺
Digital signal processing, digital output	☹	☺
Galvanic isolation	😐	☺
Power consumption	☹	☺
Long term experience	☺	😐

Table 1: Relative advantages of Hall effect compared to fiber-optic current transducers

Summary

ABB's state of the art fiber-optic current sensor is a major progress in the technology of high current dc measurement in the electrochemical industry. Besides its unprecedented performance, it opens up totally new data acquisition capabilities for high dc current process lines. The simple installation of the FOCS allows retrofitting this new measuring system to already existing plants with little restrictions on where to place the measuring heads. It represents a real technology leap with many opportunities for the future.

Authors

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