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Fiber-Optic Current Sensor for the Electro-Chemical Industry

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Abstract

A fiber-optic current sensor for direct currents up to 500 kA is presented. Applications include the control of the electrolysis process for the production of metals such as aluminium, copper, magnesium, etc. The sensor offers significant advantages with regard to performance and ease of installation compared to state-of-the-art Hall effect based current transducers. The sensor exploits the Faraday effect in an optical fiber and measures the path integral of the magnetic field along a closed loop around the current-carrying bus bars. The differential magneto-optic phase shift of left and right circular light waves propagating in the fiber is detected by means of a polarization-rotated reflection interferometer. Fiber gyroscope technology is employed for signal detection and processing. A new technique has been developed for packaging the sensing fiber in a flexible strip of fiber re-enforced epoxy for coil diameters up to several meters. The sensor can be installed without opening the current-carrying bus bars. Subsequent re-calibration is not necessary. Accuracy is within ±0.1% over a wide range of currents and temperatures.

1 Introduction

The production of metals such as aluminium, copper, magnesium, zinc, etc as well as of chlorine requires dc currents as high as 500 kA. The current must be measured, often with accuracy of ±0.1%, for process control and equipment protection. Conventional transducers for the measurement of high dc currents are based on the Hall effect. High precision transducers, working with magnetic flux compensation, are complex systems incorporating a magnetic core around the current-carrying bus bars, a number of Hall elements in air gaps of the core, solenoids to nullify the primary magnetic field in the core and at the Hall elements, and high gain current amplifiers to generate the solenoid currents. Installation and commissioning can be intricate and time-consuming. Often an analysis of the magnetic field distribution is necessary in order to place the transducer head such that errors due to asymmetries in the field and cross-talk from neighbour currents are minimized. Erroneous output can result for example from inhomogeneous heat dissipation in the transducer head and amplifier saturation at local field maxima or from a local reversal in the field direction caused by neighbour currents. Conventional systems weigh up to 2000 kg and consume up to 10 kW of power.

In the following a highly accurate fiber-optic current sensor (FOCS) is presented for rated currents up to 500 kA. The sensor overcomes the drawbacks of the classical transducers and offers superior performance and functionality. The sensor is a spin-off of a current sensor for applications in high-voltage substations [1]. The main differences concern the sensor head. Whereas in high-voltage substations the conductor cross-sections are relatively small, in the electrowinning industry the required sensor head diameters can be as large as several meters. The packaging of the sensing fiber should be flexible in order to facilitate transport and installation. Yet, the sensor calibration should remain stable well within 0.1% under repeated handling of the fiber so that recalibration of the sensor after it has been installed can be avoided.

2 Sensor Configuration

The sensor exploits the Faraday effect in fused silica fiber. The magneto-optic phase shift is detected by means of a polarization-rotated reflection interferometer [2, 3]. A fiber gyroscope module [4] is employed for interrogation (**Fig. 1**). The two forward propagating light waves, emerging with parallel linear polarizations from the lithium niobate phase modulator of the gyro module (grey box), are combined to orthogonal waves in a polarization maintaining fiber coupler. The coupler has a 90°-offset in the fiber orientation at the splice of one of its two entrance leads. The orthogonal linear polarizations are converted into left and right circular polarizations at the entrance to the sensing fiber coil. A short section of elliptical-core fiber acts as a quarter-wave retarder. At the coil end the light waves are reflected and then retrace the optical path with swapped polarizations. The returning orthogonal waves are split

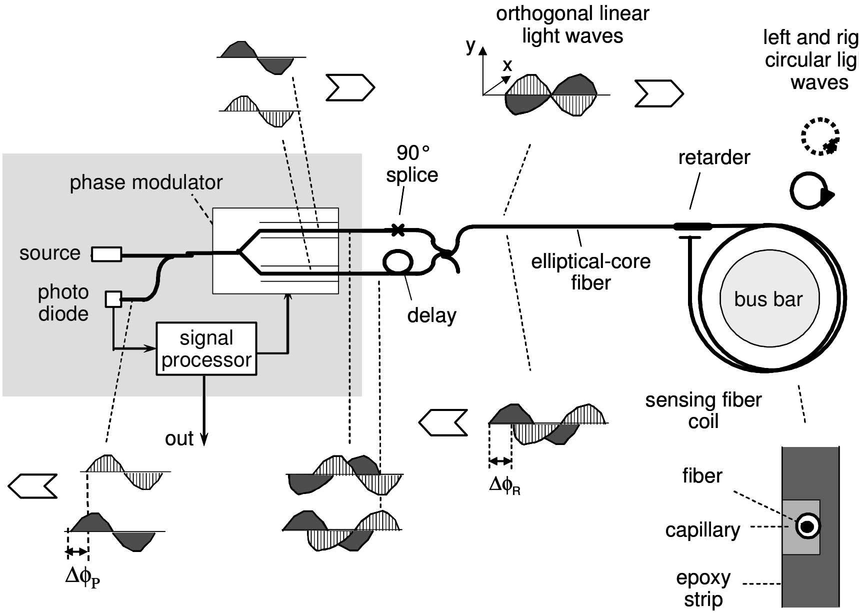

Fig. 1 Fiber-optic current sensor.

at the coupler into the upper and lower branches of the circuit. The waves polarized parallel to the transmission direction of the polarizing modulator, having traveled along reciprocal paths (vertical polarizations in Fig. 1), are brought to interference. The waves with non-reciprocal paths (horizontal polarizations) are blocked. In addition, these waves are prevented from interference by means of the delay loop in the lower branch. The roundtrip optical path lengths of these waves differ by twice the delay length, which is much longer than the coherence length of the light source. This arrangement allows one to interrogate a reflective sensing coil with a standard fiber gyroscope module.

The roundtrip differential magneto-optic phase shift in the sensing fiber corresponds to the path integral of the magnetic field along the fiber and is given by $\Delta\phi_P = 4VNI$. Here, V is the Verdet constant (2.65 µrad/A at a wavelength of 820 nm for fused silica fiber), N is the number of fiber loops, and I is the current. The gyro module has a closed-loop detection circuit including an integrated-optics lithium niobate phase modulator. A control signal is fed back to the modulator to compensate the current-induced optical phase shift. The control signal varies linearly with the applied current and also serves as sensor output. The minimum detectable optical phase shift is a few µrad/$\sqrt{\text{Hz}}$. With a single loop of fiber a phase shift of 5 µrad corresponds to a current of about 1 A. The maximum detectable phase shift is 2π rad and corresponds to a current of 600 kA.

The interface electronics provides three different output signal formats: a digital output with 24 bit resolution (with a standard protocol) and a data rate of 4 kHz as well as analog current and voltage outputs (0(4)-20 mA and 0(0.2) -1 V).

For high stability and accuracy of the sensor it is important that the light waves in the sensing fiber maintain their circular polarization states. Stress on the fiber would alter the polarizations and must be avoided. The sensing fiber is a nominally low-birefringent fiber. Here, a single loop is already sufficient. The bend-induced birefringence is small at the large loop diameters considered here. The bare sensing fiber (diameter 80 µm) resides in a thin capillary of fused silica (inner diameter 530 µm, inset in Fig. 1). The capillary protects the fiber from external stress. The capillary contains a lubricant to avoid internal friction during handling and is embedded in a thin strip of fiber-reinforced epoxy. The strip serves as a robust protection of the capillary and, with the aid of appropriate markers, allows one to perfectly and reproducibly close the fiber coil, that is to install the coil such that the retarder and reflector coincide resulting in a perfect closed-loop integration of the magnetic field. Furthermore, the strip makes it possible to install the sensing fiber and retarder with a defined and reproducible azimuth orientation with respect to the plane of the coil. As experiment and theory show this is of importance if reproducibility within 0.1% is to be reached without onsite re-calibration. The retarder is prepared such that it compensates for the temperature dependence of the Faraday effect ($0.7\text{x}10^{-4}\,°\text{C}^{-1}$) [1].

The packaged sensing fiber is accommodated in a modular housing, consisting of segments of fiber reenforced epoxy (**Fig. 2**). The housing is mounted to the current-carrying bus bars.

3 Sensor Performance

Fig. 3 shows the sensor output as a function of current in the range between 3 and 300 kA as well as the deviation of the data from linearity. The sensor coil had one fiber loop with a diameter of 1.34 m. The current

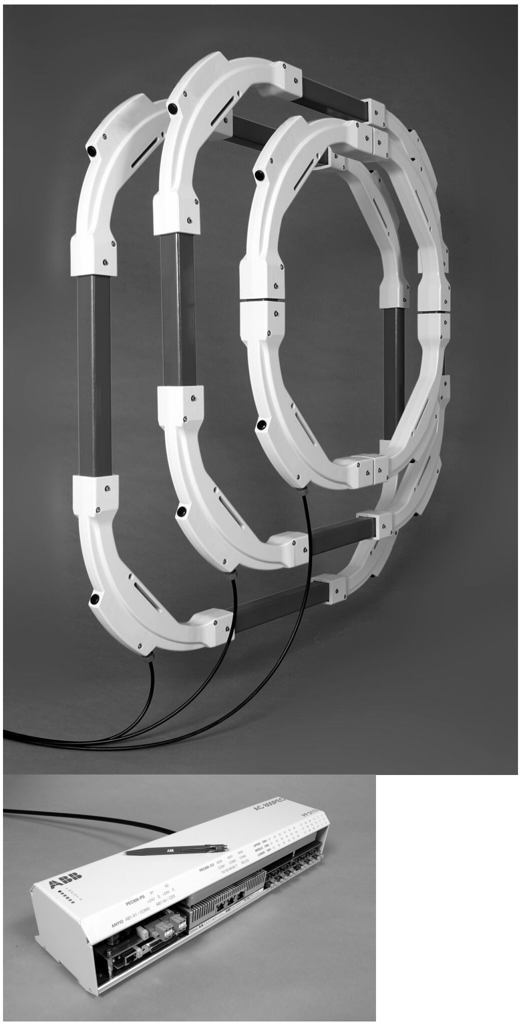

Fig. 2 Sensor heads for different rated currents (top) and electronics (bottom). The outer diameter of the smallest head is about 90 cm.

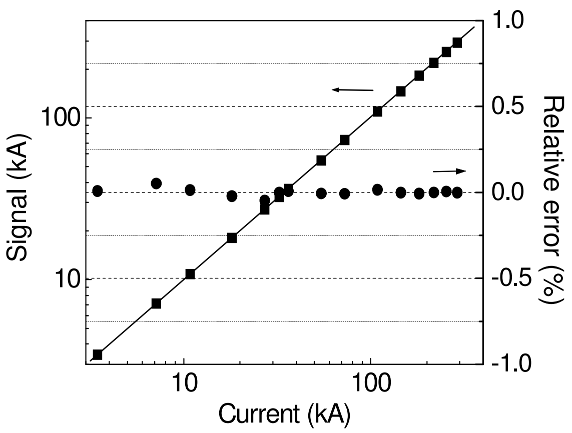

Fig. 3 Signal vs current (squares) and relative deviation from linearity (dots).

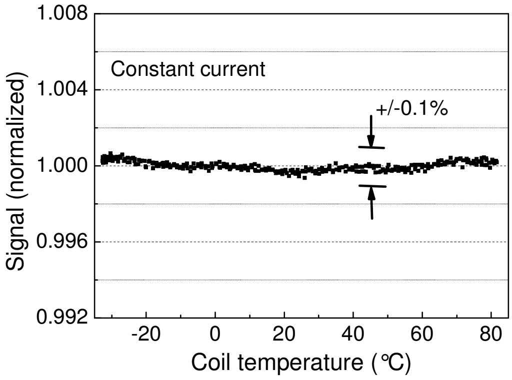

Fig. 4 Signal at constant current vs coil temperature.

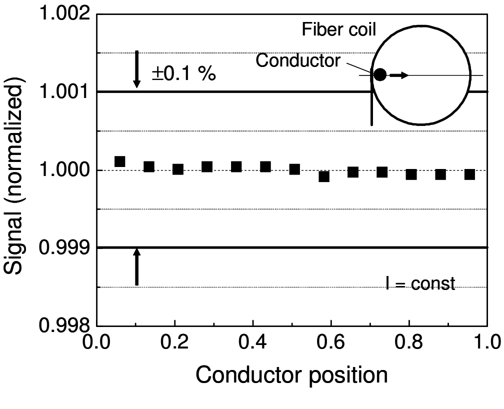

Fig. 5 Signal at constant current vs conductor position inside fiber coil. The position is given in fractions of the coil diameter.

was generated by means of 180 loops of a copper cable wound around the packaged fiber. The deviations of the data points from a straight line are less than ±0.1 %. It should be noted that retarders deviating from 90° (in case of a temperature-compensated coil) or having imperfect 45° orientation introduce some minor nonlinearity in the signal versus current relationship [1]. The signal processor corrects such effects however.

Fig. 4 shows the signal versus coil temperature for a temperature compensated coil at a constant current (1690 A). The signal is independent of temperature within less than ±0.1%, here from –35 to 80°C. The temperature range of operation of the source and detection module is from –25 to 55°C with analog interfaces and 0 to 55°C, if a digital interface is included.

As a result of the integration of the magnetic field along a closed loop around the conductor the sensor correctly measures the current independent of the particular field distribution or currents in the neighborhood. **Fig. 5** shows the signal versus the lateral position of the conductor cross-section inside the fiber coil (circular coil with a diameter of 1.34 m, conductor diameter ~70 mm). The current was

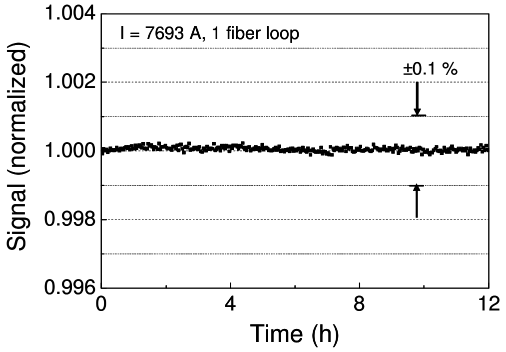

Fig. 6 Signal vs time at a constant current (7693 A).

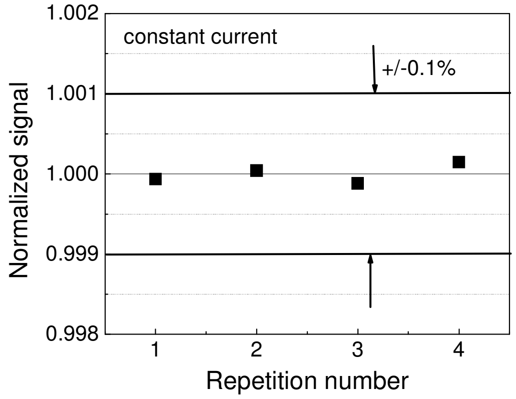

Fig. 7 Reproducibility of sensor calibration at repeated mounting and demounting of sensing coil.

constant at 2.4 kA. The variation in the signal with conductor position is within ±0.01 %, even with the conductor fully off-center and close to the retarder/reflector (most critical position). Moving the conductor around the outside of the fiber coil did not produce any signal above noise.

Fig. 6 shows the signal over a 24-hour period, again at a constant current (7693 A, data at intervals of 5 minutes, 1 s signal averaging time). The signal is stable well within ± 0.1 %. This stability was observed also over extended periods.

Another crucial point is the reproducibility of the signal after repeated handling and bending of the flexible strip containing the sensing fiber. Such handling will be necessary for transport and installation. It is advantageous if the sensor does not need recalibration after installation. To verify the reproducibility of the calibration, the packaged sensing fiber was properly mounted (1 loop, diameter 1.34 m) and the signal measured for a given current (20.8 kA). Subsequently, the coil was demounted, wrapped up as for transport, mounted again as a closed loop and the measurement repeated for the same current. The procedure was repeated several times. The signal is reproduced within small fractions of 0.1% (**Fig. 7**).

4 Conclusions

A fiber-optic current sensor for the measurement of dc currents up to 500 kA in the electro-chemical industry has been developed. The sensor has accuracy within 0.1% over a wide range of currents (at least two orders of magnitude) and temperatures. Compared to conventional dc current transducers the sensor offers a number of inherent advantages with regard to performance and ease of handling including the following: Asymmetric magnetic field distributions, e.g. in case of angled conductor arrangements, or in the presence of neighbour currents do not deteriorate the sensor performance. Magnetic centring of the sensor head is therefore not critical. Saturation by local field maxima cannot occur. Bidirectional current measurement is standard. The large bandwidth enables the detection of current ripple and recording of transients, and the digital output will lead to new data acquisition and processing possibilities. The weight and complexity of the sensor head is drastically reduced. Installation is straightforward. Power consumption is negligible.

5 Literature

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