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Fiber-optic dc current sensor for the electro-winning 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 aluminum, 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. A novel scheme of a polarization-rotated reflection interferometer and fiber gyroscope technology is used to measure the magneto-optic phase shift. 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.

Keywords: Current measurement, fiber-optic current sensor, current transducer, optical fiber devices, Faraday effect, electro process, high power conversion.

1. INTRODUCTION

The production of metals such as aluminum, 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 rather 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 neighbor currents are minimized. Erroneous output can result for example from inhomogeneous heat dissipation in the measurement head and amplifier saturation at local field maxima or from a local reversal in the field direction caused by neighbor currents. Conventional systems consume up to 10 kW of power and weigh up to 2000 kg.

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 electro-winning 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] connected to a fiber gyroscope module (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

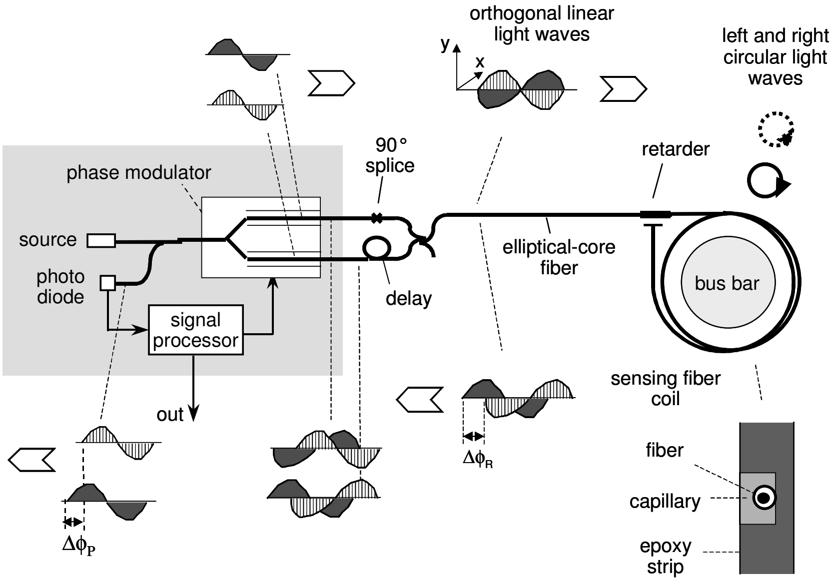

Fig. 1 Fiber-optic current sensor.

with swapped polarizations. The returning orthogonal waves are split 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 novel configuration allows one to interrogate a reflective sensing coil with a standard fiber gyroscope module. Previous sensors of this type worked with birefringence modulation, which however requires a different phase modulator.

The sensing fiber is a nominally low-birefringent fiber. In most applications a single loop is already sufficient. The bend-induced birefringence is small at the large loop diameters considered here. However, it is very crucial that any stress from the packaging is carefully avoided in order to achieve the required accuracy and stability. Furthermore, we experimentally and theoretically found that the azimuth orientation of the retarder and the sensing fiber with respect to the plane of the coil must be defined if the sensor signal is to be reproducible within 0.1%. The total birefringence, and the hence the sensor signal at a given current, vary with the azimuth angle (180° period), if the fiber is rotated around its longitudinal axis. Whereas the axis directions of the bend-induced birefringence remain fixed (determined by the plane of the coil), the axes of any residual intrinsic fiber birefringence follow the rotation. Sensitivity to fiber orientation is increased, if the quarter-wave retarder deviates from $\pi/2$. The retarder is prepared for temperature compensation of the Faraday effect[1] (0.7×10^{-4} °C^{-1}) for applications where the maximum magneto-optic phase shift is below about $\pi/2$ (corresponding to about 150 kA for one fiber loop). At higher currents the compensation effect diminishes and an extra temperature sensor is employed.

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 silicone oil 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. Furthermore, the strip makes it possible to install the sensing fiber and retarder with a defined and reproducible azimuth orientation. The packaged sensing fiber is accommodated in a modular housing, consisting of segments of fiber re-enforced epoxy (Fig. 2). The housing can be mounted to the bus bars. The gyroscope module with a 820 nm source, closed-loop detection, and digital electronics has been adapted from a commercial fiber gyroscope. Application-specific interface electronics has been added providing three different output signal formats: a digital output with 24 bit resolution and 4 kHz data rate as well as analog current and voltage outputs (0(4)-20 mA and 0(0.2) -1 V). (The electronics box shown in Fig. 2 also houses the control electronics of high power rectifiers).

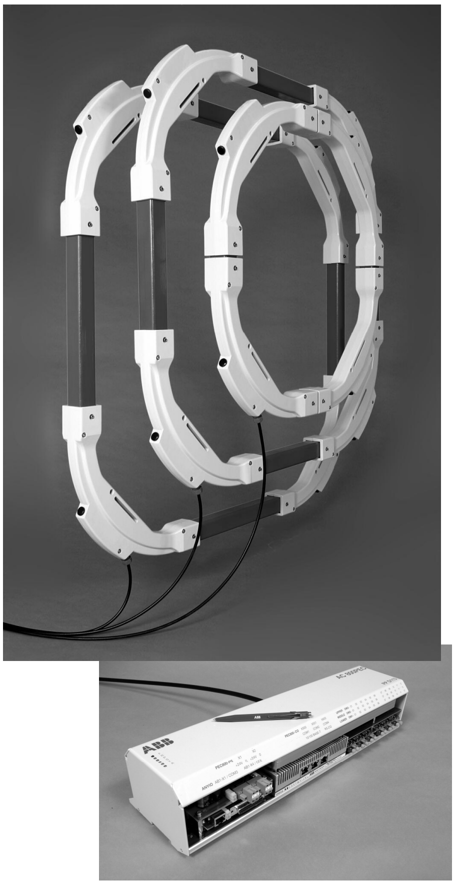

Fig. 2 Sensor heads for different rated currents (top) and electronics (bottom). The outer diameter of the smallest head is about 90 cm.

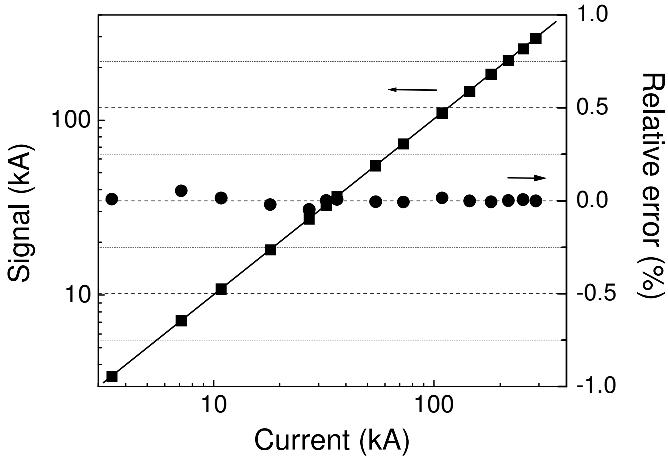

Fig. 3 Signal vs current (squares) and relative deviation from linearity (dots).

3. EXPERIMENTAL RESULTS AND DISCUSSION

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 has one fiber loop with a diameter of 1.34 m. The current was generated by means of 180 loops of a copper cable wound around the packaged fiber. A current of 300 kA corresponds to a magneto-optic phase shift of about π rad. The minimum detectable current is about 1.2 A / √Hz. The deviations of the data points from a straight line are less than ±0.1 %. The maximum detectable magneto-optic phase shift can be set as π or 2π (corresponding to about 300 or 600 kA with fiber loop). It should be noted that retarders deviating from 90° (e. g. in case of a temperature compensated coil or due to manufacturing tolerances) or having imperfect 45° orientation introduce some minor nonlinearity in the signal versus current relationship.[1] The signal processor corrects such effects, if any, however.

With temperature compensation of the Faraday effect the sensor output is independent of temperature within ±0.1% for coil temperatures between –40 and 80°C. The temperature range of operation of the electronics is -25 to 55°C with analog outputs and 0-55°C if a digital interface is added.

Fig. 4 shows the importance of defining the azimuth orientation of the retarder and sensing fiber with respect to the plane of the fiber coil. The signal at a fixed magnetic field or current was measured as a function of the azimuth angle, β, first with the sensing fiber straight, and subsequently with the fiber closed to coils with one and two loops. The loop radii were of 0.82 and 0.41 m, respectively. The retarder had been set to 103° for temperature compensation of the Faraday effect. The signal is independent of β for the straight fiber, whereas it periodically varies within 0.5 and 2.1% for the coils. The experimental data are in excellent agreement with theoretical results based on a Jones matrix description of the light propagation (solid lines).

An important advantage of fiber-optic current sensors compared to their conventional counterparts is the perfect path integration of the magnetic field. The sensor is such not affected by asymmetric field distributions and cross-talk

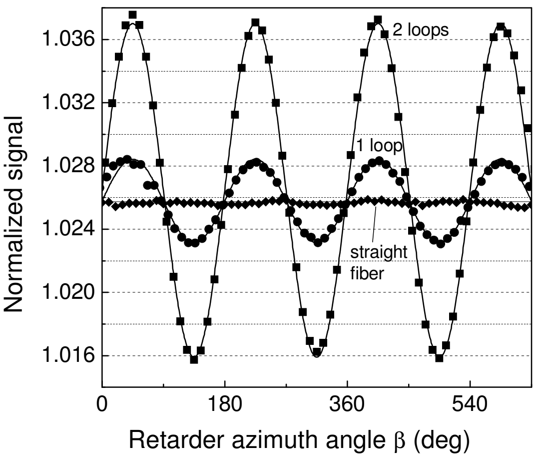

Fig. 4 Signal vs. azimuth angle of the 103°-retarder for straight sensing fiber and fiber coiled to one and two loops (experiment and theory).

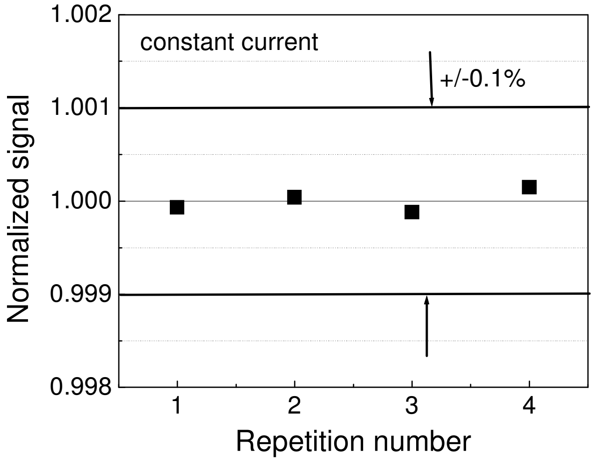

Fig. 5 Reproducibility of sensor calibration at repeated mounting and demounting of sensing coil.

from neighbor current. This gives much more flexibility in the placement of the sensor head. For an experimental verification a current conductor (diameter 70 mm) was displaced in a stepwise manner within the cross-section of a circular fiber coil (diameter 1.34 m). Moving the conductor from the coil center to fully eccentric positions affected the signal by much less than 0.1 %. The same was found for an elliptical shape of the coil (axes ratio 2:1). Moving the conductor around the outside of the fiber coil (with a current flow of 2.4 kA) did not produce any signal above noise.

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. As Fig. 5 shows, the signal is reproduced within small fractions of 0.1%.

4. CONCLUSION

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 neighbor currents do not deteriorate the sensor performance. The magnetic centering 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. The sensor will be commercially available early in 2005.

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