A PORTABLE FIBER OPTIC CURRENT SENSOR

E. Shafir
Soreq Nuclear Research Center
Yavne, ISRAEL 70600

A. Ben-Kish N. Konforti and M. Tur
Tel-Aviv University, Tel-Aviv, ISRAEL 69978

ABSTRACT

We present a ruggedized portable fiber-optic Faraday-rotation current sensor, that exhibits good and stable performance characteristics. The sensor has been tested and calibrated against a commercial induction-coil type device. The resultant scale-factor is in a very good agreement with the theoretical one, calculated following extensive fiber birefringence measurements. The measured sensor noise equivalent current is 0.23Amp/√Hz.

1. INTRODUCTION

Measurement of high currents is an essential task in high power and plasma laboratories, power distribution facilities etc. These measurements are usually carried out by a set of conventional probes which are based on various physical properties and cover only part of the current amplitudes and pulse-widths regimes. Most current probes are metallic and therefore may disturb the system being measured. Still another problem is the insulation from high voltage sources. A very promising and elegant approach to overcome these limitations is to develop a sensor made of dielectric materials.

It has long been realized \(^1\) that Faraday-rotation fiber-optic current-sensors can indeed serve as such high current measurement devices. According to the Faraday effect a longitudinal magnetic field in the direction of propagation of a beam of polarized light, causes rotation of the polarization plane. For a fiber loop one gets, according to both Faraday and Amper laws, that the total polarization rotation is proportional to the current flowing through the loop. Basic systems demonstrating the effect, as well as different modifications introduced to overcome some inherent limitations were successfully demonstrated in laboratory environments\(^2,3\).

In this work we present the development and construction of a portable engineering model of a fiber-optic Faraday rotation current sensor utilizing micro-optics components. The optical sensor has been extensively tested and its readings were compared both with those of standard current probes and with a theoretically derived transfer function. The device shows good and stable performance characteristics, which fit very well the theoretical expectations.

2. THEORETICAL ANALYSIS

Figure 1 is a schematic drawing of the sensor which comprises two parts connected by a two-fiber cable: an all-dielectric "sensing head" and an electronic module which includes the light source and detector. The light beam propagating down the input single-mode fiber is plane polarized by the first polarizer located in the sensing head, and then propagates along the low-birefringence sensing fiber which encircles the current carrying conductor an integral number of turns (N). Due to the Faraday effect, the
Figure 1: Schematic drawing of the optical sensor

magnetic field generated by the electrical current imposes a rotation of the polarization plane along the sensing fiber. This rotation is detected by the combination of a second polarizer (also in the sensing head), an output multi-mode fiber and a detector in the electronic module. Note, that the input and output polarizers are mounted in the sensing head as close as possible to each other, ensuring a practically closed loop geometry. This results in a true response to the net current flowing through the loop as well as maximum immunity to other magnetic fields not originating from currents flowing through the loop.

The net rotation angle induced by the Faraday effect at the sensing fiber can be written as:

\[ \theta = V \int H \cdot dl = NVI, \tag{1} \]

where \( V \) is the Verdet constant whose value for the silica fiber used is 2.89 \times 10^{-4} \text{rad/Amp} at a source wavelength of \( \lambda = 820 \text{nm} \), \( H \) is the magnetic induction field, \( N \) is the number of fiber loops, and \( I \) is the detected current.

In the ideal case, when the light propagates along the fiber loops its polarization plane rotates only as a result of the circular birefringence introduced by the magnetic field. In practice however, other phenomena can affect the polarization state such as, for example, linear birefringence caused by intrinsic manufacturing imperfections, by transverse pressure applied to the fiber, or by bending the fiber. While the first two can be substantially reduced by using a low birefringence fiber and careful winding procedure, the bending induced birefringence is inevitable since the optical fiber must encircle the electrical conductor. This bending induced birefringence is given by:

\[ \rho = \frac{0.85}{\lambda} \frac{r^4}{R^2} 2\pi R N, \tag{2} \]

where \( \lambda \) is the source wavelength and \( r \) and \( R \) are, respectively, the fiber and loop radii.
For maximum sensitivity and current polarity indication it is common to orient the input and output polarizers parallel and at 45° (respectively) to the bending induced birefringence axes. In so doing, the system transfer function calculated by the Jones formalism is

\[ V_{\text{out}} = \frac{1}{2} A P_0 \left( 1 + \left( \frac{2 \theta}{\phi} \right) \sin \phi \right) ; \quad \phi^2 = (2 \theta)^2 + \rho^2. \] (3)

\( \theta \) and \( \rho \) are respectively the current induced circular birefringence (Faraday effect) and the bending induced linear birefringence. \( V_{\text{out}} \) is the detector amplifier output voltage, \( P_0 \) is the source power, and the power losses, detector responsibility and the various amplifications have all been lumped into the constant \( A \).

In the low current regime (up to approximately 20KAmp for our sensor) and for a reasonable bending radius (R \( \approx \) 10cm), \( \theta \ll \rho \) and Eq. (3) reduces to

\[ V_{\text{out}} = \frac{1}{2} A P_0 \left( 1 + \frac{\sin \rho}{\rho} \right) = \frac{1}{2} A P_0 S \] (4)

where \( S \) is the system scale factor, given by

\[ S = \frac{1}{2} A P_0 \left( \frac{\sin \rho}{\rho} \right) 2N = \frac{1}{2} A P_0 \left( \frac{\sin(\beta N)}{\beta} \right) 2N \] (5)

and \( \beta = \rho/N \) is the linear birefringence per turn.

In this regime the output power is linearly proportional to the current flowing through the loop. Since the Verdet constant in fibers is very small, and as can be seen from Eq. (5), the presence of bending induced birefringence further reduces the system scale factor by a factor of \( \sin \rho/\rho \), it is essential to choose the appropriate configuration in which maximum sensitivity is obtained. According to Eq. (5), the scale factor is proportional to \( \sin(\beta N) \) rather than to \( N \) and sensitivity will be maximized when \( \sin(\beta N) = 1 \). For \( \lambda = 820 \text{nm}, r = 62.5 \mu \text{m} \) and \( R = 75 \text{mm} \), it follows that the maximum achievable scale factor (and thus maximum sensitivity) will be obtained for \( N = 4 \) or 5.

3. CONSTRUCTION AND CHARACTERIZATION

In order to evaluate our theoretical analysis a setup for linear birefringence measurements was constructed, utilizing a Sosil-Babinet compensator (SBC). The SBC is a linear retardation plate whose retardance can be continuously varied. The measuring system comprised a GaAs diode laser, a detector, input and output polarizers, an optical fiber wounded N times around a 75mm radius quartz ring (used also in the final device) and the SBC. The SBC retardance was set so as to compensate exactly for the bending induced retardation (birefringence) introduced by the wound fiber. This way the bending induced birefringence was measured for various number of fiber loops (N) and the optimal value of N was found to be 3, in contrast to the theoretical expectation of 4 or 5 based on Eq. (2). The measured value of \( \rho \) for \( N = 3 \) was 0.47\( \pi \), which is very close to the optimal value of 0.5\( \pi \).

Following the construction (see Fig. 2) the sensor was tested with alternating currents of various amplitudes and frequencies and with high current pulses. Figure 3 shows the device response to a typical 40KAmp pulsed current (upper curve) compared to the output signal of a Rogowski coil which is currently the common tool for pulsed high current measurements (lower curve). The points in Fig. 4 represent the sensor output signal at various generating currents. As was expected, at the low current
Figure 2: The fiber optic current sensor

regime (≤20K Amp) the sensor response is linear, exhibiting a scale-factor of S=4.15mv/K Amp. Based on Eq. (4) and knowing the DC output voltage and the value of the linear birefringence ρ (0.47π) the theoretical scale-factor for relatively low currents was calculated to be 4.30mv/K Amp, which is very close to the measured value stated above. According to the calculated transfer function the sensor output signal increases monotonically with its generating current up to approximately 80K Amp. Beyond this value currents can in principle still be measured utilizing more sophisticated signal processing system.

Figure 3: A typical 40K Amp pulse measured by the fiber optic sensor (upper curve) and by a conventional induction coil (lower curve)
As for the low current regime, the minimum detectable current of the optical sensor is dictated by the ever present noise at the detector output. In our sensor the design was such that the dominant noise component is the source noise which lies some -120dB/Hz below the DC output level, resulting in a measured noise-equivalent-current of 0.23Amp/√Hz, i.e., 140Amp for our sensor configured for a 380KHz bandwidth.

In Fig. 5 the upper and lower curves show the optical sensor and the Rogowski coil responses (respectively) to a low frequency (=100Hz) alternating current signal with $I_{max}=1.3$KAmp. As can be seen the induction coil failed to reproduce the flat portions of the square wave due to magnetic saturation effects, while the optical sensor continued to faithfully follow the true current signal. Note also that whereas DC or quasi DC currents are not measurable with the magnetic induction based devices, the optical sensor is, in principle, capable of such measurements.

4. SUMMARY

A ruggedized, portable fiber optic Faraday rotation current sensor was designed and constructed. The sensor comprises an all-dielectric sensing head containing all the optical polarization components, and a separate electronic module that includes the source and detector. The two modules are connected by a special two-fiber cable. The results of the sensor characterization are consistent with the theoretical expectations, demonstrating a noise equivalent current of 0.23Amp/√Hz (i.e. 140Amp at 380KHz bandwidth). The device transfer function, being linear up to 20KAmp, is monotonic up to approximately 80KAmp. Much higher currents can in principle be measured by incorporating a more sophisticated signal processing scheme. In addition, the advantages of the optical sensor over standard sensors were discussed and partly demonstrated.
Figure 5: Response of the optical sensor (upper curve) and the induction coil (lower curve) to a low frequency generating current (~100Hz, 1300Amp). The induction coils suffers from saturation effects

REFERENCES


