Study of the stability of the fiber-optic current sensor

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Abstract. Optical fiber sensors are of particular interest for applications in the high-voltage environments of the electric power industry due to their characteristic properties including dielectric nature, immunity to electro-magnetic interference, and small size and weight. We have studied current sensor that employs the Faraday effect in the spun fiber and signal processing based on the additional harmonic modulation of the self-consistent polarization interferometer. We replaced the traditional PZT transducer with the LiNbO\textsubscript{3} waveguide electro-optical modulator that allowed to increase significantly the modulation frequency and to reduce the length of the fiber delay line. Original error compensation methods allowed us to achieve the accuracy of ±0.2\% in amplitude in the temperature range of about 50 °C.

1. Introduction

Modern energetics requires the measurement of the voltages and currents of industrial frequency with the uncertainty of not more than 0.1-0.05\% [1]. Measuring current transformers (MCT), designed to measure large values of currents (hundreds-thousands of amperes) by a multiple reduction by means of induction converters to values suitable for measuring devices, have been successfully used for more than a century, but have a number of significant drawbacks introduced by the nonlinearity of the core magnetization characteristics, especially with strong changes in the primary signal during the transition processes in the controlled network (starting currents, emergency processes).

As a result, the industry required new types of converters based on different physical processes than transformation through magnetically coupled windings. These are fiber-optic current sensors (FOCS). But despite the achievements, this technology still faces a number of difficulties. First of all, the specialists are striving for increasing the accuracy and reducing the cost of ready-made solutions, which requires scientific research to improve both the optical scheme and processing algorithms [2-6].

2. Principle of operation

The object of the study is FOCS, working on the Faraday Effect, built on the known optical scheme, in which an additional phase modulation by a harmonic signal is used to detect the signal [7-8]. It is also known that the optical power of the signal at the input of the photodetector is the sum of the harmonics of the modulation frequency. In this case, only even harmonics are present at rest, and in the presence of a magnetic field created by an electric current, there are also odd harmonics of the modulation frequency. The used method of signal demodulation in such current sensors is a synchronous detection of the first and second harmonics of the modulation frequency and analysis of their relationship [9].

As a result, the output signal of FOCS is determined by the following formula
\[ \Delta \psi_F^r = \arctg \left[ \frac{j_2(\psi_m')}{j_0(\psi_m')} \cdot \frac{U_1(\psi)}{U_2(\psi)} \right] \quad \text{where } \psi_m = \psi_m' \]

(1)

where \( \Delta \psi_F \) and \( \Delta \psi_F^r \) – real and calculated Faraday phase shifts, \( \psi_m \) and \( \psi_m' \) - real and defined modulation amplitude, \( U_1 \) and \( U_2 \) – the first and second harmonics of the modulation frequency, \( j_k(\psi_m) \) are Bessel functions of the first kind of the \( k \)-th order.

3. Compensation of the result dependence on the modulation amplitude

The formula (1) shows that the calculated phase shift will coincide with the actual measured only when everything is perfectly matched and the modulation amplitude taken into account in the calculations is equal to the real amplitude of modulation. But as a rule, due to external conditions, the real modulation amplitude is not constant and an error occurs when calculating by formula (1). From here there are problems: to define optimum value of modulation amplitude and to compensate the error arising at any uncontrollable deviations of modulation amplitude from optimum value.

The solution of these problems has been described in detail in [10]. The optimal modulation amplitude was chosen to be \( \psi_{opt} = 2.629874 \) radian, and to eliminate the error caused by an instability of the modulation amplitude, a compensation algorithm was developed in accordance with the formula (2)

\[ \Delta \psi_F^r = \arctg \left[ \frac{U_1}{U_2} \cdot \left( 1 + k_1 \left( \frac{U_2}{U_4} - K_0 \right) + k_2 \left( \frac{U_2}{U_4} - K_0 \right)^2 + k_3 \left( \frac{U_2}{U_4} - K_0 \right)^3 \right) \right] = \]

\[ = \arctg \left[ \frac{j_1(\psi_m)}{j_2(\psi_m)} \cdot g(\psi_m) \cdot tg(\Delta \psi_F) \right] \]

(2)

where \( U_1 \), \( U_2 \), \( U_4 \) - the first, second, fourth harmonics of the modulation frequency, \( k_1 \), \( k_2 \) and \( k_3 \) - compensating coefficients, \( g(\psi_m) \) – error correction function

\[ g(\psi_m) = 1 + k_1 \left( \frac{j_2(\psi_m)}{j_4(\psi_m)} - K_0 \right) + k_2 \left( \frac{j_2(\psi_m)}{j_4(\psi_m)} - K_0 \right)^2 + k_3 \left( \frac{j_2(\psi_m)}{j_4(\psi_m)} - K_0 \right)^3 \]

(3)

\[ K_0 = \frac{j_2(\psi_m_{opt})}{j_4(\psi_m_{opt})} = 5.30176 \]

(4)

To implement the developed method of the FOCS signal detecting, the fourth harmonic of the modulation frequency was additionally extracted and a compensation block was added to the signal processing algorithm.

4. Assembling the model of the fiber-optic current sensor

In addition to improving the metrological characteristics of the FOCS, the actual task of this work is also to reduce the cost of such sensors. The FOCS scheme described in [10], contains a delay line made of birefringent PM fiber, the length of which is about 1 km. Length of the delay line is associated with modulation frequency \( f_0 \) by ratio

\[ l = \frac{1}{\tau f_0} \]

(5)

where \( \tau = 5 \) us/km – light delay in propagation in an optical fiber.

Piezoelectric transducer (PZT) used as phase modulator works effectively at the resonance frequency, which is about 40 kHz. This frequency corresponds to the optimal length of the delay line of 1250 m. To reduce this length, it is necessary to increase the operating frequency of the modulator, but this is practically impossible within the PZT design. Therefore, when assembling the model, we decided to use an electro-optical modulator (EOM) working on the Pockels effect instead of a PZT.
Such modulators can effectively operate at frequencies up to several gigahertz, so the frequency of additional modulation in this case is limited only by the photodetector bandwidth and the maximum frequency of the ADC. For example, by setting the modulation frequency to 400 kHz, you can reduce the length of the delay line to 125 m, which is ten times less than the length of the delay line in the original circuit described in [10].

We have assembled the model of FOCS, the appearance of which is shown in figure 1, the optical scheme – in figure 2.

During the wave propagation from the phase modulator to the mirror and back the phase of the modulating voltage should change the sign to the opposite. Therefore, given the length of the delay line and the length of the spun fiber, totaling 290 m, and according to the formula (5), the frequency of the modulating signal should be equal to 172.144 kHz. Since the signal generation of additional phase modulation and signal processing is carried out entirely in digital form in FPGA, we had to take into account the limitation of the possible values of the modulation frequency. For the selected sampling rate of 100 MHz and the data buffer volume of 2000 points, it is necessary that the buffer contains an integer number of periods of the first, second and fourth harmonics of the modulation frequency. This condition was satisfied by the modulation frequency of 150 kHz. In addition, the frequency limiting factor was the bandwidth of the photodetector used in the experiment.

For the FOCS model, software was developed in the NI LabVIEW programming environment.

5. Experimental study of the FOCS model
An algorithm for compensation of measurement errors arising due to uncontrolled deviation of the modulation amplitude from the optimal value according to the developed demodulation method was added and experimentally tested in the signal processing program of the FOCS. During the
experiments, the compensation coefficients derived from numerical simulations published in [11] were initially set: \( k_1 = -0.162354 \), \( k_2 = 0.038086 \), \( k_3 = -0.004883 \). The deviation of the modulation amplitude from the optimal value was ±10 %. The error of the readings was measured by the comparison device, \( I_{\text{nom}} = 5 \) A, the level of the supplied current is 51.1%. As a result, the dependences of the error on the deviation of the modulation amplitude without compensation and with compensation using the coefficients specified in the patent were registered (figure 3).

![Figure 3](image-url)

**Figure 3.** Measurement error vs Modulation amplitude deviation of the optimal value in the range of ±10%. Blue – compensation with coefficients during numerical simulation, orange – without compensation, black – compensation with experimentally selected coefficients.

It is seen that the behaviour of the obtained dependences coincides with the results of numerical modelling presented in [11]: in the range of deviation of the modulation amplitude from the optimal value \( \psi_m \) by ±10%, the demodulation error without compensation is ±15%, while for the method of the FOCS signal demodulation according to the formula (2) using the correction function (3), the demodulation error does not exceed ±2.5%.

In addition, the experimental selection of compensation coefficients providing the minimum error due to the deviation of amplitude modulation in the process of FOCS operation was also carried out. As a result, the coefficients of the best compensating error, was equal to: \( k_1 = -0.140137 \), \( k_2 = 0.029297 \), \( k_3 = -0.005859 \). On the basis of the figure 3 it can be seen that with the selected coefficients the demodulation error is within ±1%.

The dependence of the error on the deviation of the modulation amplitude from the optimal value in the range of ±1% was also measured in detail. The results are presented in the figure 4. It can be seen that in the range of the modulation amplitude deviation from the optimal value \( \psi_m \) by ±1%, the demodulation error without compensation is ±1.8%, while for the FOCS signal demodulation method according to the formula (2) using the correction function (3), the demodulation error does not exceed ±0.2%. The algorithm of demodulation of the FOCS signal containing a compensation block with the coefficients selected during the experiment showed the best result: when the modulation amplitude deviates from the optimal value in the range of ±1%, the detection error does not exceed ±0.1%.
Figure 4. Measurement error vs Modulation amplitude deviation of the optimal value in the range of ±1%. Blue – compensation with coefficients during numerical simulation, orange – without compensation, black – compensation with experimentally selected coefficients.

In addition to the instability of the modulation amplitude, there is another significant source of errors: the temperature dependence of the optical elements of the FOCS scheme [12-16]. The most sensitive element to temperature changes is the fiber quarter-wave plate. We conducted an experimental study of the demodulation error dependence on the temperature of the quarter-wave plate. To do this, as a heating and cooling device, we used the Peltier element, and the temperature was measured using a thermocouple. The quarter-wave plate was heated from 10°C to 53°C, and then cooled in the same temperature range. Experimental studies have shown that, indeed, when the temperature of the quarter-wave plate changed, demodulation error increased, and the behavior of this dependence coincided with the behavior of the dependence of the amplitude of the second and fourth harmonic of modulation frequency on the temperature of the quarter-wave plate. Based on the obtained temperature dependences, we compensated demodulation error caused by the change in the quarter-wave plate temperature using the amplitude of the second harmonic of the modulation frequency. As a result, the demodulation error did not exceed ±0.2% in the temperature range of the quarter-wave plate from 10°C to 53°C (figure 5).

Figure 5. Relative current error vs Fiber quarter-wave plate temperature.
We also investigated the nonlinearity of the transfer characteristics of FOCS at different values of the measured current. The obtained dependence is shown in figure 6.

![Relative current error vs Measured current](image)

**Figure 6.** Relative current error vs Measured current.

It can be seen from the figure 6 that with the growth of the measured current the demodulation error became more stable.

### 6. Conclusion

As a result of this work, the FOCS model was assembled and configured, in which the PZT was replaced with the electro-optical modulator, the modulation frequency was increased and the length of the delay line was reduced. Original error compensation methods allowed us to achieve the amplitude accuracy of ±0.2% in the temperature range of about 50 °C.

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