Temperature influence on measurement uncertainty of optical current sensors

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Abstract. This paper presents the main influences of temperature on optical current sensor measurement uncertainty. The optical current sensor considered is based on the Faraday effect and has a polarimetric detection scheme. Some uncertainty contributions are quantified, and other contributions that are more difficult to be quantified are presented and discussed.

1. Introduction

Optical current sensors (OCSs) offer attractive features such as wide bandwidth, lightweight and small size, adjustable turn-ratio, integrated functions (e.g., voltage and current sensing in one device), as well as safety and environmental benefits when used in power systems (elimination of oil or gas insulation, no open secondaries, and no ferro-resonance) [1, 2]. Due to these key characteristics, OCSs can replace conventional current sensors in power systems, as current transformers (CTs). However, measurement accuracy and long-term operation stability are under continuous research to support their further development. Some external factors, such as temperature, vibration and stray magnetic fields cause errors that are difficult to overcome in a practical OCS [3].

Temperature is one of those factors that affects all devices, leading to measurements deviations. Measuring devices are usually set or calibrated at a reference temperature, for example, 20°C. As the temperature varies, the measuring devices and their components change, leading to degradation of measurement uncertainty. This is the case with OCSs, where the stability of optical sources, optical materials and optoelectronics are highly affected by temperature variations.

This paper presents an analysis of the influence of temperature on the measurement uncertainty of optical current sensors based on the Faraday effect and that use polarimetric detection scheme. Section II describes the basic principles of these optical current sensors. Section III shows the most important concepts associated with estimating measurement uncertainty. Section IV analyzes the main uncertainty contributions from the influence of temperature on the behavior of optical current sensors. Finally, Section V presents some conclusions.

2. Optical current sensor

OCSs are usually based on Faraday effect and Ampere loop theorem, that is, polarized light with different polarization states in a material with magnetic optic properties has different propagation speed under the action of a magnetic field generated by current, resulting in polarization plane rotation of polarized light [4]. The Faraday rotation angle θ_F resulting from propagation of the light wave along a path L under the action of a magnetic field B is given by (1), where V is the Verdet constant, an intrinsic property of the material, expressed in [rad/ (m.T)] and that depends on the wavelength λ and the temperature T [5]. The Faraday effect for a linearly polarized (LP) light wave is shown in Fig. 1.

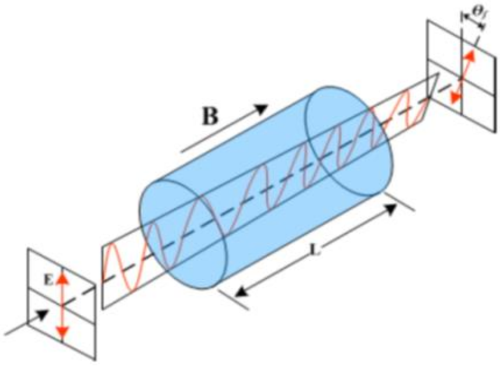

Figure 1. OCS schematic diagram [5].

$$\theta_F = \int_L V(\lambda, T).B.dL \qquad (1)$$

In an OCS, a light wave is launched from an optical source, passes through a linear polarizer, and becomes LP light. This LP light propagates through a magneto-optical material along the external magnetic field produced by the electric current to be measured (the sensor itself). The detector part of an OCS converts the measurement of the rotation angle to an electric signal through a photodetector and digitizes it through an analog-to-digital (A/D) card. A software then processes the digital signals and presents the measured current. Fig. 2 shows an OCS block diagram. Optical current sensors can be classified into two main groups: bulk sensors and fiber sensors. The first group uses a magneto-optical glass structure as a sensor element, with a high Verdet constant. The sensor can be used involving the entire conductor of the current to be measured or only part of it. The second group is the fiber optic sensor, where the sensor element is the fiber itself. The main advantage of these sensors is the possibility of involving the entire conductor of the electric current to be measured, making it insensitive to external magnetic fields. Depending on the group of sensor, bulk or fiber, the sources of uncertainty can be significant, including uncertainties due to the temperature.

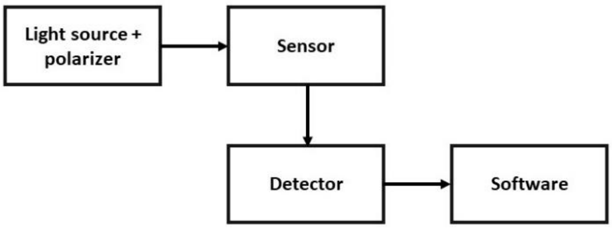

Figure 2. OCS block diagram.

3. Measurement uncertainty evaluation

Reference [6] sets out general rules for evaluating and expressing the measurement uncertainty that are intended to be applicable to a wide range of measurements. The uncertainty of the result of a measurement reflects the lack of exact knowledge of the value of the measurand. The terms error and uncertainty are often confused - they are complementary but distinct. It is assumed that the result of a measurement has been corrected for all recognized significant systematic effects and that every effort has been made to identify such effects. Sometimes it may be impractical to correct for a systematic effect, so you may decide to model this effect as a source of uncertainty. The result of a measurement after correction for recognized systematic effects is still only an estimate of the value of the measurand because of the uncertainty arising from random effects and from imperfect correction of the result for systematic effects [7].

4. Temperature influence on measurement uncertainty

Temperature contributes to OCS measurement uncertainty due to the following mechanisms: (a) temperature variations produce fluctuations in the Verdet constant of the optical material; (b) temperature fluctuations change the wavelength of light generated by the light source, thus modifying the Verdet constant of the sensor and the θ measured by the OCS; (c) optoelectronics components used in the OCS, as photodiodes and data acquisition units, have their response changed by temperature variations; (d) birefringence of the optical material varies with temperature variations.

For estimation of uncertainty contributions due to temperature variation, the temperature range must be defined according to the intended use of the OCS. If the OCS is to be used outdoors, then the ambient temperature variation must be estimated. The graph in Fig. 3 shows the measurement of temperature variation, in 15 min intervals, through an entire day in September, in the city of Belém, Brazil. The difference between higher and lower temperatures is about 14 °C. Fig. 4 shows the daily maximum and minimum temperatures during 2022, and the higher difference is about 15 °C [8]. These differences can be used as the temperature range in uncertainties estimation, but it is important to note that if the sensor is exposed to sunlight, the temperature variation can be even greater.

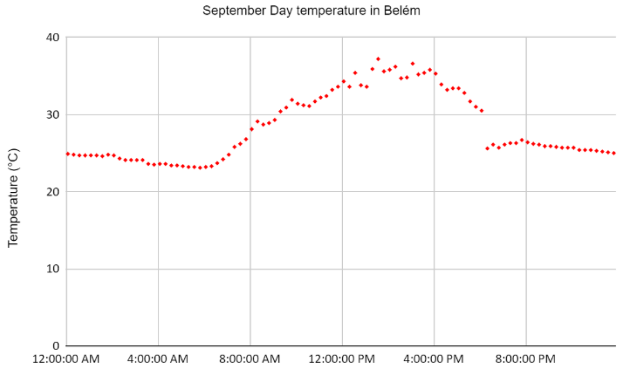

Figure 3. Measured temperature in a September entire day in Belém, Brazil.

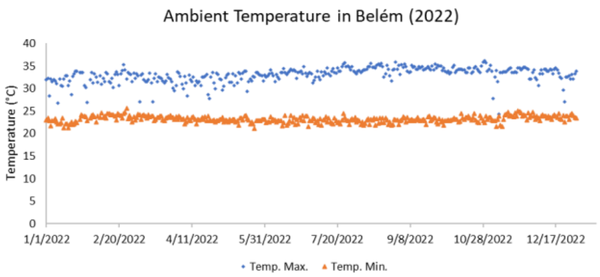

Figure 4. Daily temperature in Belém, Brazil in 2022.

4.1. Optical Material

Reference [9] shows the Verdet constant change with temperature for SiO_2 and SF 57 glass. The change in product *VL* the change in product *VL* per unit of temperature *d(VL)/dT*, assuming a uniform magnetic field and no birefringence, can be defined by (2), where *V* is the Verdet constant, *L* is the length of the sensor, V_0 and $(VL)_0$ are the values at 20°C, and $\alpha = (dL/dT)/L$ is the thermal expansion coefficient of the glass for the range of temperatures tested. The SF 57 glass product *VL* will change about +0.3% with approximately +15 °C variation.

$$\frac{1}{(VL)_0}\frac{d(VL)}{dT} = \frac{1}{V_0}\frac{dV}{dT} + \alpha \qquad (2)$$

4.2. Light Source

The stability of the mean wavelength of optical source affects the uncertainty of an OCS, as Verdet constant changes with wavelength variation. References [10, 11] show the Verdet constant dependence on the wavelength for various optical materials (glasses). This dependence can be seen in (3), where λ is the wavelength, and a, b and λ_{0v} are the fitting parameters. Fig. 5 shows the dependence of SF 57 glass Verdet constant on wavelength.

$$V = \frac{\pi}{\lambda}\left\{a + \frac{b}{\lambda^2 + \lambda_{0v}^2}\right\} \qquad (3)$$

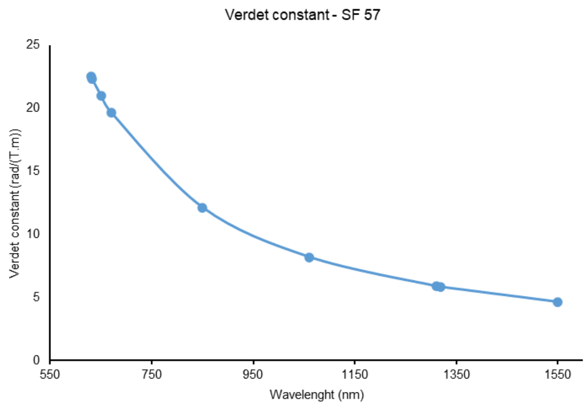

Figure 5. SF 57 glass Verdet constant dependence on wavelength.

The mean wavelength of the optical sources depends on the temperature. Reference [12] measured the mean wavelength variation of a SLD from 15 °C to 45 °C. When the temperature changes, the varying tendency of the mean wavelength is in a linear fashion. The change in the wavelength per °C, $d\lambda/dT$, is about +0.6 nm in the 1310 nm region. For a +15°C variation, λ will change about +9 nm. This deviation on λ will drift *V* by -0.06 rad/ (T.m), or -1.0% on the 1310 nm region of a SF 57 glass sensor. As the mean wavelength of the light sources varies, the Verdet constant of the optical material also varies, changing the Faraday rotation angle and the OCS response.

4.3. Optoelectronics

A/D cards have their uncertainties known at calibration temperature (usually between 20 °C and 25 °C). As they are used a few degrees Celsius beyond the calibration temperature, additional uncertainties must be considered. It is a good practice to use manufacturer's information available in manuals, datasheets, or other documents to estimate uncertainty due to temperature variation. For a NI

A/D card model 6009, according to its manual, accuracy is 0.07% at 25°C and 0.7% for the full temperature range [13]. In this case, if it is necessary to reduce the uncertainty due to temperature, measurements should be performed to evaluate a temperature coefficient and use it as a correction factor. The same analysis must be done for the photodetectors. For a Thorlabs photodetector model PDA100A, its manual states a 2% accuracy at 25°C, and no information about temperature variation effects, then measurements must also be conducted to evaluate a temperature coefficient.

4.4. Birefringence
In a material with birefringence characteristics, polarization orthogonal components of the incident light wave travel at different velocities, due to different refraction indexes in each direction of the material. If the incident light is LP, then the polarization state can change from linear to elliptical. If the birefringence of the optical material changes the polarization state of a LP light, errors and uncertainties arise in the measurement of the rotation angle of an OCS. The amount of uncertainty due to the birefringence can be evaluated using special techniques in the Faraday rotation angle measurement algorithm or software. Furthermore, the birefringence of the optical material varies with temperature variations [14, 15].

5. Conclusion
This article presented the main ways in which temperature influences the measurement uncertainty of optical current sensors used in power systems. The temperature variation directly modifies the Verdet constant of the optical material, and indirectly, as it modifies the average wavelength of the light source, with the Verdet constant depending on the wavelength of the light. These variations increase the measurement uncertainty of optical current sensors, degrading their quality. Temperature variation also affects the behavior of the optoelectronic components and the birefringence of the optical material. Depending on the target measurement uncertainty for the sensor, different procedures should be adopted for modeling the uncertainty contributions due to temperature, such as measuring the temperature coefficient of the A/D cards or accurately determining the temperatures range in which the optical current sensor will be used.

For future work, the quantification of all uncertainty contributions due to temperature and the estimation of the total uncertainty due to temperature, and the evaluation of how much it impacts on the total measurement uncertainty in applications with an optical current sensor remain.

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References
[1] Li Y, Zhang W, Liu X and Liu J 2019 *Applied Sciences* **9**
[2] Larruskain M, Valverde V, Torres E, Buigues G and Santos-Mugica M, 2018 *Renewable Energy and Power Quality Journal* **1** 310315
[3] Samimi M, Akmal A and Mohseni H 2015 *IEEE Sensors Journal* **15** 47214728
[4] Wu J and Zhang X 2020 *Proc 7th Int. Forum on Electrical Engineering and Automation (Hefei, China)* pp 134-143
[5] Silva R et al 2012 *Applied Sciences* **2** 602628
[6] *Evaluation of measurement data — Guide to the expression of uncertainty in measurement - JCGM 100:2008 - GUM 1995 with minor corrections* 2008.
[7] Cohen E 1996 Error and Uncertainty in Physical Measurements *Modeling Complex Data for Creating Information. Data and Knowledge in a Changing World* ed Dubois JE and Gershon N (Berlin, Heidelberg: Springer) pp 55-64

[8] Brazilian National Institute of Meteorology 2022 Weather data history. Available online: https://portal.inmet.gov.br/dadoshistoricos (accessed on 8 June 2023).
[9] Williams P, Rose A, Day G, Milner T and Deeter M 1991 *Appl. Opt.* **30**
[10] Hoffmann H 1992 *J. Physique IV*
[11] Weber M 2002 *Handbook of Optical Materials* (Boca Raton: CRC Press)
[12] Chen X, Jiang L, Yang M, Yang J and Shu X 2019 *J. Phys.: Conf. Ser.* **1300** 012047
[13] NI USB-6009 Specifications. Available online: https://www.ni.com/docs/en-US/bundle/usb-6009-specs/page/specs.html (accessed on 9 June 2023).
[14] de Boer J, Hitzenberger C and Yasuno Y 2017 Polarization sensitive optical coherence tomography - a review [Invited] *Biomed Opt Exp* Available online: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5480584/ (accessed on 9 June 2023).
[15] S. Cheng et al. 2015 *Appl. Opt.* **54** 1000910017