DOI 10.5162/SMSI2025/B4.3

Fiber Optic Current Sensor System for Long-Term Monitoring of Geomagnetically Induced Currents in the Power Grid

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Summary: Within this work, we describe an interferometric fiber optic current sensor for the monitoring of geomagnetically induced currents in power grids. For the first time, the developed system is able to provide information about the distribution of these currents on individual phases and lines on high-voltage potential. During preliminary testing, a current sensitivity in the mA range was achieved. For in-field operation, the system was equipped with a custom electronics unit to enable on-board data processing, data storage as well as remote data access.

Keywords: fiber optic current sensor, geomagnetically induced current, Faraday effect, Field Programmabable Gate Array, power grid monitoring

Introduction

Monitoring the components of our electric power system is of great significance in order to ensure proper functionality and network stability. In particular, power transformers in the electric grid are affected by low frequency, (quasi-)direct currents (LFCs), disturbing the operating point of the device and causing half-cycle saturation as well as increased heating and reactive power demand. One well-known origin of LFCs is space weather, where the interaction of charged solar particles with the Earth's magnetosphere leads to so-called geomagnetically induced currents (GICs) on ground level.
At the moment, GICs are only monitored in transformer neutral points [1] and there is no information about their distribution on the grid's three phases and on individual lines, which would facilitate the choice of appropriate mitigation measures. While conventional current transformers suffer from several shortcomings, fiber optic current sensors (FOCS) based on the Faraday effect offer a practical solution for this task, given their ability to simultaneously measure alternating (ac) and direct (dc) currents with high bandwidth as well as being galvanically separated from the circuit, allowing their installation on high-voltage potential [2]. A current-related magnetic field in parallel to the propagation direction of light in a dielectric medium will lead to a rotation of the light's plane of polarization. For a closed fiber loop around a conductor, the resulting phase shift can be described by

$$\phi = VNI \tag{1}$$

where the Faraday phase shift ϕ is directly proportional to the current I through the Verdet constant V of the material and N, the number of fiber windings around the conductor.

Sensor setup

The used sensor setup (Fig. 1) is based on the polarization-rotated reflection interferometer [3] and exploits the non-reciprocity of the Faraday effect. The relative phase shift ϕ_r between two orthogonal light waves completing a forward and backward travel in the system will then be four times higher than described with (1).

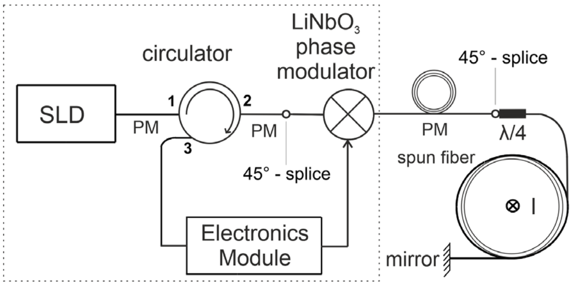

Fig. 1: Optical sensor setup of FOCS: SLD - superluminescent diode, PM - polarization-maintaining fiber leads, λ/4 - fiber quarter wave retarder, I - current-carrying conductor

Linear-polarized light from a superluminescent diode (SLD) at 1550 nm with a bandwidth of 60 nm is used to equally excite both slow and fast axis modes of a polarization-maintaining (PM) fiber at a 45° splice point. A birefringent $LiNbO_3$ phase modulator introduces a non-reciprocal phase shift between the two axes. The following PM fiber lead separates the two modes beyond their coherence length to minimize cross-coupling. A fiber $\lambda/4$ retarder transforms the two orthogonal linear polarization modes into left- and right hand circular polarizations, which then acquire a non-reciprocal phase shift twice caused by current's magnetic field on their round trip. Due to the interchange of polarization axes at the mirror, the optical setup is reciprocal and immune to perturbations experienced by both modes. An ideal modulation is achieved, when one full period of the sinusoidal modulation signal is equivalent to the time of flight for the light in the interferometer. The Faraday phase shift can then be inferred from the detected harmonics of the modulation frequency [3]. On their return trip, the two polarization modes are again mixed at the first 45° splice, one axis is blocked by going through Port 3 of the PM circulator and the optical signal is sent to the electronics module for signal processing.

The developed electronics module takes over the entire data processing from initial detection,

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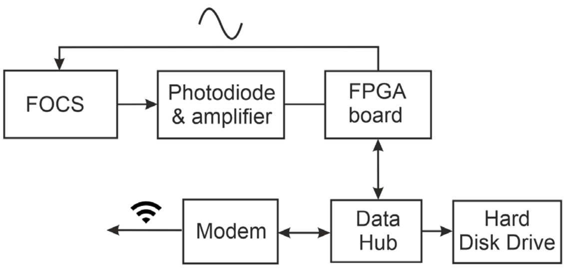

Fig. 2: Block diagram of electronic signal processing and data storage for the installed FOCS system.

calculation as well as data storage. In a first stage, the optical signal is converted into an electrical signal by a photo diode and then amplified. The FPGA (Field Programmable Gate Array) board contains an analog-to-digital converter and calculates the Faraday phase shift ϕ_r. Using a digital-to-analog converter, the $LiNbO_3$ phase modulator is controlled. The FPGA chip communicates via Ethernet with a commercial data hub (Artemes GmbH, Austria), allowing storage of data on a local hard disk drive and remote access via OpenVPN.

Application

The developed system was tested in a laboratory setting with a reference current source to determine its sensitivity regarding dc and ac, as well as their superposition. A sensing head with a radius of $R = 8$ cm and $N \approx 150$ achieved a dc detection limit of around 0.2 A (Fig. 3). Measurements at lower currents are affected by optical noise and an imperfect λ/4 retarder. As demonstrated in [4], a sinusoidal ac will show as a rectified sensor signal and a superimposed dc will lead to a shift of the ac peaks. For an ac signal with $I_{peak} = 300$ A, the standard deviation was 0.5 A, putting a limit on the detectable dc biases.

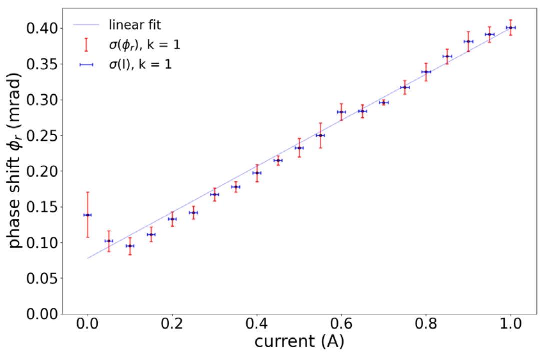

Fig. 3: Dc characteristic of developed FOCS from 0-1 A at room temperature: σ - standard deviation, k-factor = 1

The FOCS was installed at an electrical substation in Vienna, Austria. The optical elements as well as the electronics module (casted area in Fig. 1) were mounted in an electric cabinet next to the transformer and are kept at a constant temperature of 25° C. The fiber optic coil was placed on one phase of the 220 kV side of a Ynyn0 transformer. To fit the transformer turret, a new sensing head with a radius of $R = 24$ cm

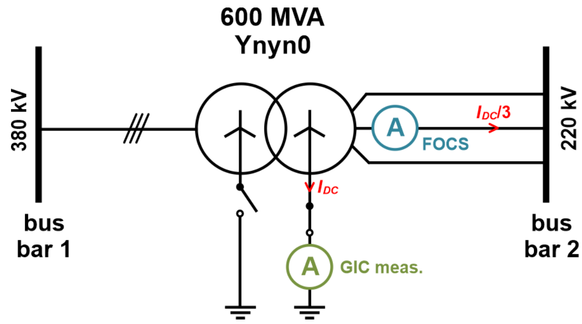

Fig. 4: Schematic of FOCS installation on one phase of a 600 MVA Ynyn0 transformer and comparison to a reference zero-flux GIC measurement system in the transformer neutral point.

was constructed, resulting in $N \approx 50$. A reference zero-flux current transducer measures direct currents in the transformer neutral point (Fig. 4).

Outlook

Given the current stage of the solar magnetic activity cycle, a frequent occurrence of GICs in the Austrian power grid with magnitude of several amperes is expected. The installed fiber optic sensor system will for the first time allow a direct measurement of GICs on the individual phases, and enable a comparison to ongoing GIC measurements in the transformer neutral point. The measurement campaign is planned for several months with the goal of monitoring the effects of geomagnetic storms on the power grid. In a follow-up study, the presented sensor setup will be improved by correcting temperature-induced performance variations in the sensor signal caused by a temperature-dependent Verdet constant and birefringence of the sensing fiber and an imperfect $\lambda/4$ retarder.

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