Self-powered signal conditioning circuit for an HVDC optical current sensor

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Abstract— This paper presents an optical current sensor (OCS) for HVDC networks. The proposed OCS combines electrical signal conditioning circuit and a low voltage transducer (LVT) based on piezoelectric and photonic technologies. The characterization of the OCS individual components was performed in laboratory conditions and the sensor operation was evaluated based on the current measurement range set by the IEC 61869-14 standard. The experimental results demonstrated that the device can be used under the input current range conditions specified in IEC 61869-14 and has the potential to provide current measuring functionality in challenging locations that impose limitation on conventional sensors.

Index Terms— Fiber Bragg Grating (FBG), Optical current sensor (OCS), optical voltage sensor, High Voltage Direct Current (HVDC) networks, Low voltage transducer (LVT).

I. INTRODUCTION

High Voltage Direct Current (HVDC) networks are a significant component of modern electrical power systems, enabling the efficient transmission of electricity over long distances and interconnecting asynchronous alternating current (AC) power grids. HVDC technology offers several advantages over traditional AC transmission, such as lower transmission and resistive losses, enhanced controllability and stability, enabling efficient power flow control, higher energy density, and improved grid operation [1]–[3].

As opposed to AC grid protection, the HVDC protection requires current and voltage measurements over extended distances with fast reaction times from the protection systems [4]. Fast response that is an order of magnitude greater than for AC equivalents, is mandatory to meet disconnection times better than 30 ms and to provide timely mitigation of faults [5].

A range of shunt and magnetic-based DC current sensors such as fluxgate and Hall effect sensors have been introduced in the past decades. Magnetic-based sensors are widely adopted by industry; however, shunt-based sensors have the advantage of accuracy, range and lower thermal drift [6], [7]–[9]. The use of a shunt has the added advantage of producing sufficient voltage and power to drive an energy scavenging unit. Sensors combining fiber Bragg gratings (FBGs) and giant magnetostrictive materials (GMM), such as Terfanol-D, have been proposed [10]. Although these sensors are suitable for multiplexing, they suffer from nonlinearity and saturation problems affecting their measurement accuracy [9], [11]. Fiber-optic current sensors (FOCSs) based on Faraday effect could achieve high measurement accuracy (down to 0.1%); however, they suffer from environmental vulnerability when interrogated over long distances [9], [11], [12]. Lumiker's OCS technology based on faraday effect overcomes the vulnerabilities listed above, at the expense of a complex optical system when multiplexing is involved [13].

To provide alternative solutions to the existing technologies, it was proposed that distributed voltage and current metering and wide-area network protection can be realized using novel photonic sensor systems facilitating improved network visibility and ensuring fast reaction while remaining cost competitive. Therefore, we previously proposed a range of optical voltage and current sensors for metering and protection applications in AC networks and evaluated their performance according to the relevant IEC standards [4], [14]. We demonstrated that the devices have the potential to meet the accuracy requirements set by the IEC standards and when interrogated remotely they can provide functionality that is not attainable with the conventional voltage and current transformer [10], [13].

This paper reports on the capabilities of a novel optical current sensor (OCS) for HVDC networks. The proposed OCS combines electrical signal conditioning circuitry and a low voltage transducer (LVT) based on piezoelectric and photonic technologies. The sensor is self-sustaining and passive without any need for providing an addition external power source and easily multiplexable and suitable for remote interrogation. The characterization of the OCS individual components was performed in laboratory conditions and the sensor operation was evaluated based on the current measurement range requirements set by the IEC 61869-14 standard for DC current transformers (DCCT) which represent the most recent standard for DCCT [14].

II. Measurement Requirements

The nominal (rated) current for HVDC lines can range from 1 kA to several kA [15], [16]. The current flowing in the conductor can deviate from the nominal conditions and drop to very low levels or it can reach values several times greater than the nominal current during electrical fault events. Consequently, the current measurement device needs to be capable of measuring current in the line accurately within the required range.

The required current amplitude (ratio) error limits set by the IEC 61869-14 standard for measurements with DC current transformers (DCCT) are detailed in Table 1. In Table 1, the K_{pcr} and K_{ALF} factors are the rated extended primary current factor and the accuracy limit

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factor, respectively. The standard values of K_{ALF} are 3, 6, 10, and 20 [17]. For the purpose of this investigation, a K_{ALF} of 3 was selected. Therefore, it is expected that the operation of the proposed sensor should comply with the above requirements within the current range between 5% and 300% of the nominal value.

Table 1. Limits of ratio error for DCCT as per IEC 61869-14 [17].

Accuracy Class	Ratio Error (±%) at current (% of Rated)				
	5	20	100	K_{pcr}	K_{ALF}
0.1	1	0.25	0.1	0.1	1
0.2	2	0.5	0.2	0.2	2
0.5	3.5	1	0.5	0.5	5
1	5	2	1	1	10

III. OPTICAL CURRENT SENSOR

A. Sensor Concept

The proposed sensor concept is shown in Fig. 1. A low resistance shunt capable of producing a nominal voltage of 50 mV at the nominal line current is employed as a current-to-voltage converter. The voltage signal generated across the shunt is amplified by a dedicated low-power precision operational amplifier (op-amp) to drive a low voltage transducer (LVT) combining piezoelectric and photonic technologies. The op-amp is powered from an energy harvester scavenging energy from the shunt. Thus, the optical sensor is self-sustaining and passive without any need for providing an additional external power source.

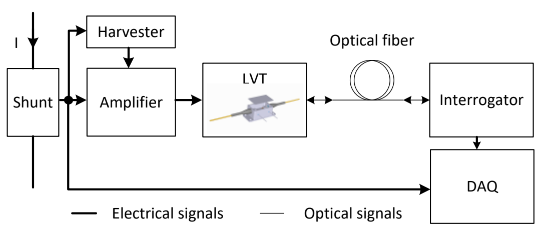

Fig. 1 HVDC Sensor Concept

Due to the stringent operating characteristics expected from the sensor, its individual components with very low power profile were selected to meet the required conditions as described in the following sections. Additionally, Fig. 1 depicts a data acquisition system used to characterize the sensor in the laboratory as reported in Section IV.

B. Low Voltage Transducer

The LVT comprises a low voltage piezoelectric transducer (PZT) built using a multilayer PICMA stack [18], and a fiber Bragg grating (FBG) sensor inscribed into a single-mode fiber which is suspended across the PZT as shown in Fig 2. The transducer is housed in an industry-standard, hermetically sealed butterfly package with voltage provided to the piezoelectric stack through two Kovar pins.

Under the influence of external electric field due to the measured voltage, the electrical energy is converted to mechanical strain in the PZT, which is then measured optically by an FBG.

As the grating pitch is altered by strain, a change in the peak wavelength of the reflected light can be detected by an FBG interrogator.

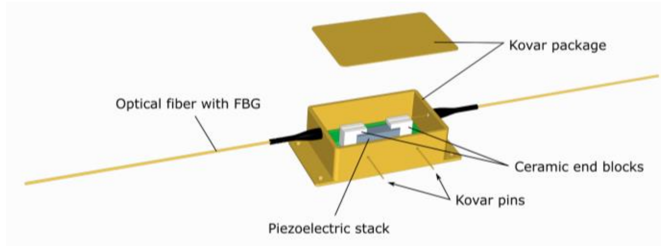

Fig. 2 Low Voltage Transducer [18]

By tracking the FBG peak wavelength, the voltage input can be reconstructed. By considering the current-to-voltage conversion, the optical signal can be calibrated in terms of the current.

The LVT selected for this investigation is a reliable PZT actuator comprised of a PICMA P-885.51 stack with dimensions 5×5×18 mm, which can retain 96% of its displacement after 10^{11} cycles [19], and has the operating voltage range between -30 V and 120 V, a capacitance of 1.5 µF, and a resonant frequency of 70 kHz. A nominal voltage of 1 V was selected for the LVT.

C. Precision Amplifier

To ensure an appropriate strain-to-voltage response of the LVT, a sufficiently high voltage needs to be provided across the PZT component. Since the nominal voltage of the LVT is 1 V, the signal from the shunt resistor needs to be amplified. To comply with the power budget of a dedicated energy harvester, which operates in the milliwatt range, the amplifier component was carefully chosen. Consequently, TSU111, a single-supply rail-to-rail sub-micro Watt power consumption integrated IC with a maximum current of 900 nA, a typical gain-bandwidth product of 11.5 kHz, and open loop gain of 120 dB with a supply rail limitation of 5 V, was selected to satisfy the stringent operating requirements.

D. Energy Harvester

The considered energy harvester utilizes a boost converter LTC3108 which is an integrated DC/DC converter IC. It can scavenge energy from extremely low input source from as low as 20 mV to 400 mV, constructed with other associated network of components. It has a selectable output voltage of 2.2 V, 3.3 V and 5 V, and a maximum output current of 4.5 mA. The output current is a function of the coupled inductor/transformer type used in the design, with the 1:20 unit delivering highest output current of approximately 4 mA; however, with a minimum input voltage limitation of 100 mV. In this design, a coupled 1:100 inductor was chosen, suitable for an input voltage as low as 20 mV, complying with the expected input voltage, albeit with a trade-off of lower current output of around 700 µA.

IV. EXPERIMENTAL RESULTS

A. Experimental Setup

To characterize the signal conditioning circuit and the proposed optical current sensor (OCS), the experimental setup was arranged as shown in Fig. 1. The shunt voltage was emulated using a resistive voltage divider comprising a 100 Ω and 2 Ω resistors powered from a variable DC voltage source. The emulated shunt voltage was then amplified and monitored by the LVT. The electrical signals in the respective points of the signal conditioning circuitry were monitored by a data acquisition (DAQ) card (NI USB 6003). The optical signals from the LVT were monitored by an I-MON USB 256 interrogator (Ibsen Photonics) which offers typical performance across the range of commercially available interrogators. Both devices were connected to a PC and the optical and electrical signals were acquired at 4 kHz.

B. LVT Characterization

To characterize the LVT, the voltage generated by the DAQ was supplied to the component input and the optical signals were captured when the input voltage was ramped up and down. The LVT responses when the input voltage was cycled up to 1 V, 3 V, and 5 V are shown in Fig. 3. Clearly, the LVT response is characterized by hysteresis loops changing their widths and rotation with the maximum voltage.

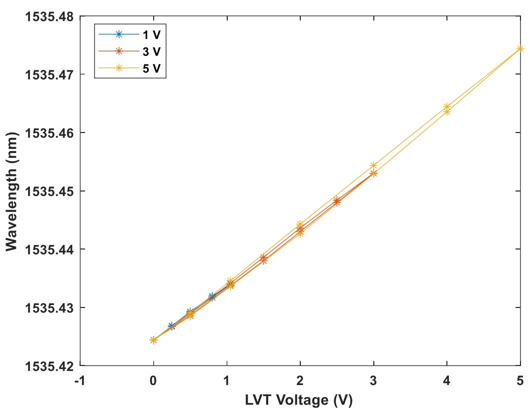

Fig. 3 LVT characteristic.

Hysteresis occurs when the balance of strain polarization changes under the influence of electric field. Due to the counter-balance of polarization strain at a particular voltage level between the forward and the reverse paths, displacement occurs [20].

Clearly, the hysteresis is narrower for lower voltages [20]–[22]. A curve fitting algorithm using linear or non-linear regression can be applied to derive the electro-optic relationship for the OCS response.

C. Amplifier Characterization

To ensure the required voltage level at the LVT, the shunt voltage was amplified by a non-inverting op-amp configuration with a gain of 21 V/V.

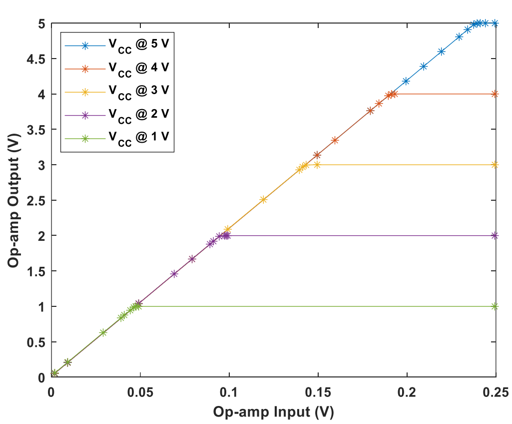

Fig. 4 Op-amp operation characteristics at different input voltage.

To ensure that the gain and the output voltage from the op-amp remain constant at the op-amp power supply fluctuations due to harvester varying output, the relevant op-amp characterization was performed. The op-amp input-output characteristics for its power supply voltages (V_{CC}) between 1 V and 5 V are shown in Fig. 4.

Clearly, the gain remained the same for different levels of the power supply voltage and the op-amp response was linear up to its saturation level.

D. Harvester Characterization

To verify the harvester capability to provide sufficient voltage to power the op-amp, it was characterized at 3.3 V and 5 V output settings and at the shunt voltage between 2.5 mV (equivalent to 5% of the nominal current) and 250 mV (500% of the nominal current). At the same time, the op-amp response was captured. The results of this investigation are presented in Fig. 5.

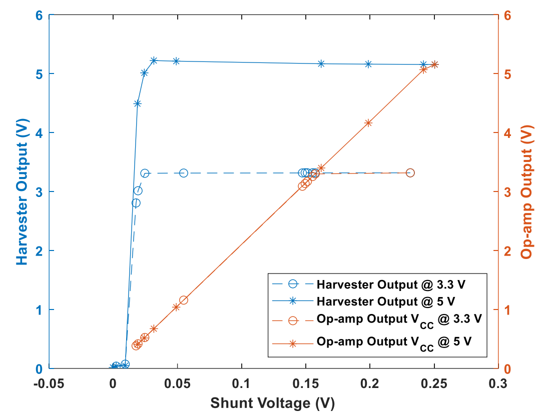

Fig. 5 Harvester and op-amp operation characteristics.

As can be seen, the maximum voltage at the harvester output was available as soon as the 20-mV level across the shunt was reached for both output settings. At the same time, the op-amp response was linear and with the required gain up to the saturation voltage at either 3.3 V or 5 V output setting of the harvester.

Yet another experiment involved verification of the harvester charging and discharging times when powering the op-amp as a function of the shunt voltage. These results are presented in Fig. 6.

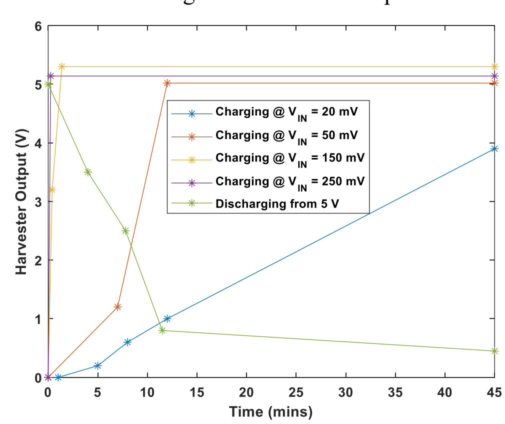

Fig. 6 Harvester charging vs time response.

In the experiment, a worst-case scenario was envisaged for the harvester, where it was totally discharged of any stored energy akin to a black start [23]. The harvester charging time to ramp up to the maximum voltage from the discharged state takes approximately 12 minutes for the nominal input voltage (50 mV). From the discharging trace in Fig. 6, it can be expected that the harvester will accommodate any voltage swing (collapse) in the system for up to 11 mins, after which time the measurements will not be possible.

According to fault regulation for HVDC networks, converters should be restored within 0.14 s to 0.25 s [24]. Many cycles of 0 to 5V step signal with a 1 ms rising edge were applied to the sensor input, and it faithfully represented it. This proposed solution is a potential option that should meet HVDC transient response timescale, and provide measurement functionalities in challenging locations.

E. Complete Sensor testing

The completed optical sensor solution was tested after completing the characterization of each of the functional block. The sensor was tested with voltages between 5% to 470% of the nominal voltage to the sensor. The results of this investigation are shown in Fig. 7.

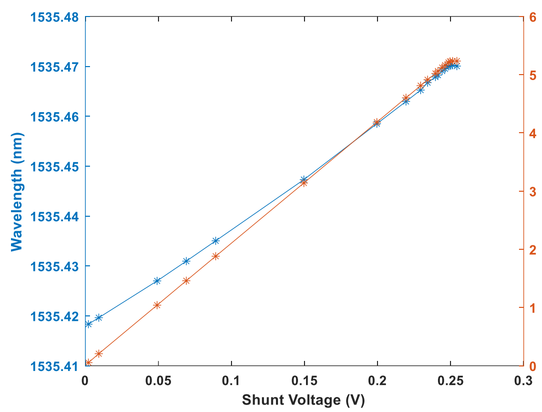

Fig. 7 Performance characteristics of the complete sensor.

By inverting data in the above plot, the sensor calibration curve can be created and the measured shunt voltage or current through the shunt can be reconstructed based on the sensor wavelength response.

V. CONCLUSION

This paper has investigated the operational capabilities of an optical current sensor (OCS) for HVDC networks. The proposed OCS combines electrical signal conditioning circuitry and a low voltage transducer (LVT) based on piezoelectric and photonic technologies. The characterization of the OCS individual components was performed in laboratory conditions and the sensor operational capabilities were evaluated based on the current measurement requirements set by the of IEC 61869-14 standard. It was shown that the signal conditioning circuitry functions as expected, providing the required signals for the LVT within the current range specified by the standard. The energy harvester provides sufficient power for the circuitry, so that the OCS remains a self-sustainable device. With its self-powering capability, it can be deployed for distributed measurements in the areas where conventional sensors are infeasible to utilize, for example in subsea cable splices.

Future work will focus on detailed accuracy and signal response tests of the proposed sensor according to the IEC 61869-14 standard.

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REFERENCES

[1] M. Barnes, D. van Hertem, S. P. Teeuwsen, and M. Callavik, “HVDC Systems in Smart Grids,” 2017.
[2] ABB, “ABB review, HVDC special report.”
[3] SP Networks, “ANGLE-DC,” 2015.
[4] G. Fusiek and P. Niewczas, “Photonic voltage transducer with lightning impulse protection for distributed monitoring of MV networks,” *Sensors (Switzerland)*, vol. 20, no. 17, pp. 1–23, Sep. 2020.
[5] Muniappan Mohan, “A Comprehensive review of DC Fault Protection Methods in HVDC Transmission Systems,” *Springer Open*, pp. 2–6, 2021.
[6] DIMITRIOS TZELEPIS *et al.*, “Voltage and Current Measuring Technologies for High Voltage Direct Current Supergrids,” *IEEE*, pp. 7–12, 2020.
[7] K. Bohnert, P. Gabus, J. Kostovic, and H. Brändle, “Optical fiber sensors for the electric power industry,” *Opt Lasers Eng*, vol. 43, no. 3–5, pp. 511–526, Mar. 2005.
[8] D. Xu, W. Sae-Kok, A. Vujanic, A. Motta, N. Powers, and T.Neo, *Fully Digital Non-conventional Instrument Transformer*. IEEE, 2019.
[9] L. Bi and H. Li, “An overview of optical voltage sensor,” in *Proceedings - 2012 International Conference on Computer Science and Electronics Engineering, ICCSEE 2012*, 2012, pp. 197–201.
[10] S. Xu *et al.*, “Optical fiber current sensors based on FBG and magnetostrictive composite materials,” *Applied Sciences (Switzerland)*, vol. 11, no. 1. MDPI AG, pp. 1–21, Jan. 01, 2021.
[11] Y.-J. Rao, “In-fibre Bragg grating sensors,” 1997.
[12] R. M. Silva *et al.*, “Optical current sensors for high power systems: A review,” *Applied Sciences (Switzerland)*, vol. 2, no. 3. MDPI AG, pp. 602–628, Sep. 01, 2012.
[13] https://www.lumiker.com/en/camos200-current-monitoring/, “CAMOS200 Current Monitoring.”
[14] Niewczas P, Fusiek G, Philip Orr, Campbell D. Booth, Adam Dyśko, and Fumio Kawano, “Distributed photonic instrumentation for power system protection,” *IEEE*, pp. 2–4, 2015.
[15] Dirk Van Hartem, Oriol Gommis-Bellmunt, and Jun Liang, “HVDC GRIDS,” 2018.
[16] Scottish and Southern Electricity Network, “HVDC Technology Capability,” 2018. [Online]. Available: www.ssen.co.uk
[17] SASO IEC 61869_14, “INSTRUMENT TRANSFORMERS-Part 14: Additional requirements for current transformers for DC applications (SASO),” 2019.
[18] P. Niewczas and G. Fusiek, “Preliminary characterisation of an optical current sensor for HVDC networks,” pp. 1–3.
[19] PI, “PZT-ACTUATORS”.
[20] H Li, Y Xu, M Shao, L Guo, and D An, “Analysis for hysteresis of piezoelectric actuator based on microscopic mechanism,” *IOP*, pp. 1–6, 2018.
[21] Jinqiang Gan and Xianmin Zhang, “A review of nonlinear hysteresis modeling and control of piezoelectric actuators,” *AIP*, pp. 1–5.
[22] G. Fusiek and P. Niewczas, “Construction and Evaluation of an Optical Medium Voltage Transducer Module Aimed at a 132 kV Optical Voltage Sensor for WAMPAC Systems,” *Sensors*, vol. 22, no. 14, Jul. 2022.
[23] Christopher Owens, “Blackout Report,” pp. 20–30, 2019.
[24] National grid, “HVDC Implementation Fault Ride Through.”