Design and Development of a Low -Cost Optical Current Sensor

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Abstract- In this paper we display the layout of a low-fee optical present-day sensor. The sensor precept is the Faraday rotation of a mild beam thru a magneto-optical material, SF2, while a magnetic discipline is present. The prototype has an excessive sensitivity and an excessive linearity for currents starting from zero as much as 800 A. The blunders of the optical fibre sensor are smaller than 1% for electric powered currents over 175 A.

Indexed Terms- Faraday rotation; plastic optical fibre; optical fibre sensors; current sensor

I. INTRODUCTION

The new makes use of of the electric community, in addition to the growing call for for more high-satisfactory of service (QoS), require offering the community with "intelligence". After the technological revolutions of the previous couple of decades, with unattainable technological advances withinside the vicinity of data and communications generation (ICT), the electric zone had changed into an anachronism the use of the generation of remaining century. One of the essential demanding situations may be to acquire data approximately the number one factors of the community at any point. Optical generation is a perfect candidate for this, without the protection requirements (disconnectors, lightning rods, etc.) of traditional sensors.

Optical modern transformers primarily based totally on optical fibre sensors at the moment are being advanced worldwide [1–4]. In contrast with traditional transformers, optical fibre modern sensors (OFCS) are compact and lightweight, smooth to install, resistant to electromagnetic noise, and that they provide a huge size variety and lengthy distance sign transmission [5–8]. To date, some of OFCS were proven to be feasible. They have true reliability and sensitivity, despite the fact that the charge is likewise excessive. This downside may be triumph over with plastic optical fibre (POF).

POFs are a reasonably-priced and sturdy opposite numbers to glass optical fibres. For quick haul programs and sensors, POFs provide many advantages, along with excessive numerical aperture, massive center diameter, ease of connection and true mechanical reliability, amongst others [9,10]. In many sensing programs, the space among the measuring factors and the electronics, consisting of the emitter and the receiver, is exceptionally quick [11–14]. This feature, in addition to its immunity to electric powered and magnetic fields, makes POFs appropriate for electric powered modern sensing [15].

The primary physics precept in the back of the sensor operation is the modulation of the polarization of mild. The rotation of the polarization vector of mild inside a obvious cloth alongside the route of an outside magnetic area become first said via way of means of Michael Faraday in 1845 [16]. An exciting element of the Faraday rotation is that the experience of rotation relative to the route of the magnetic area is unbiased of the mild route for a given cloth. Most of the sensors advanced are primarily based totally on garnets or flint glasses with a massive Verdet constant [17–19], despite the fact that a magnetic area sensor product of bulk PMMA has additionally been proposed [15].

The aim of this paintings has been the layout and improvement of a low-value optical modern sensor, consisting of its modular electronics. The novelty of the layout is two-fold: on the only hand, the optical head of the brand-new sensor makes use most effective of plastic components (POF, collimators and polarizers) to transmit and get hold of the mild from a magnetooptic glass with small extra losses. On the alternative hand, the newness of the electronics is predicated at the aggregate of a low-noise and a excessive-sensitivity layout that makes it beneficial for the size of low modern values with minimum errors.

There is a huge variety of programs of this sensor along with the manage of electrolysis technique for the manufacturing of metals, tracking of currents on overhead electric distribution lines, in underground electric vaults, currents inside Switchgear, tracking magnetic fields and fault detection programs, amongst others.

This painting has been advanced in collaboration with the Smart Grid Company of the ARTECHE group, which is devoted to the power zone. Recently, a pilot set up the use of optical fiber sensing generation become correctly commissioned at COPEL's 138 kV Posto Fiscal substation withinside the kingdom of Paraná, Brazil. In this paper, the precept of operation of the optical modern sensor may be defined first, consisting of an in-depth description of the optical head and the electronics. Afterwards, a characterization of the sensor may be given, collectively with a few examples of area outcomes with the sensor. Finally, the primary conclusions may be summarized.

II. THEORY

The Faraday impact changed into the primary magneto-optical impact to be proposed and established in fibre contemporary sensors. Figure 1 indicates a schematic configuration of the Faraday rotation. When a mild beam passes via a pitcher medium in a magnetic area, its polarization vector is circled in percentage to the area. The Verdet consistent V relates the road necessary of the magnetic area B to the rotation of the polarization aircraft of a linearly polarized, in step with the equation [20–22]

Since B is proportional to the contemporary, φ is likewise without delay proportional to the contemporary. Equation (1) states that the Faraday rotation and, hence, the sensitivity of the crystal, will increase with the Verdet consistent V and it additionally indicates that the longer the optical path (crystal rod duration d), the extra the Faraday rotation. These parameters are each crucial and supply us stages of freedom to optimize the optical head of the sensor.

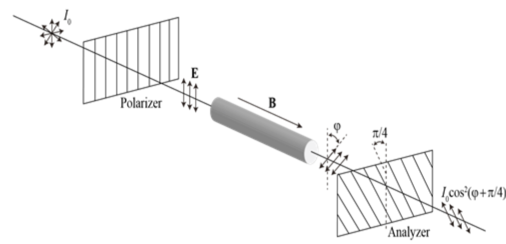

Figure 1. Faraday rotation.

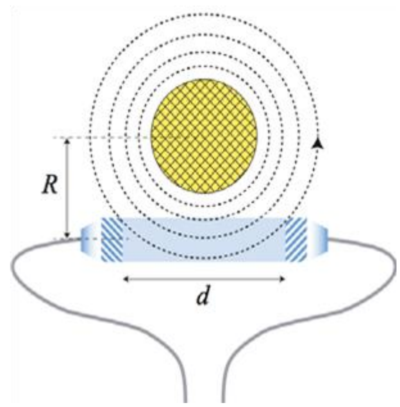

Figure 2. Geometry of our design showing the magnetic field generated by a metallic wire (yellow) around the SF2 glass rod (blue).

The Verdet regular has high-quality values for diamagnetic materials, along with the SF2 glass utilized in our layout, and poor values for paramagnetic materials [17–19]. Figure 2 depicts the geometry of our precise approach, with the glass rod positioned perpendicular to the metallic twine. The magnetic area B produced with the aid of using the cutting-edge of a steel twine is

Where in R is the space from the twine axis, i is the electrical cutting-edge a the permeability of free space [23]. If the duration of the SF2 glass rod is small enough, the magnetic area may be taken into consideration regular within the glass fabric and Equation (1) reads that is the simple equation governing the layout of the optical head in our approach.

III. DESIGN OF THE CURRENT SENSOR

Basically, the low-value present day sensor layout includes components the optical head and the accompanying electronics. This phase describes each component individually

IV. OPTICAL HEAD

The optical element is represented in Figure 3. It includes POF portions of five–10 m period, PMMA collimators with a small focal period, linear polarizer-sheets, the magneto-optic glass rod, the emitter and the receiver. The magneto-optic rod (sensing material) is a Flint glass SF2 from Schott with a Verdet steady of 11.6 rad/Tm at 632.eight nm, a diameter of five mm and a period of 20 mm. The collimators are biconvex plastic lenses with a focal period of five.four mm and an normal diameter of 7.eight mm. We additionally use an analog fibre optic transceiver, the FC300T from Firecomms, with termination for naked POF. It combines an excessive pace RCLED-primarily based totally 650 nm emitter and an excessive sensitivity PIN diode for detection [24].

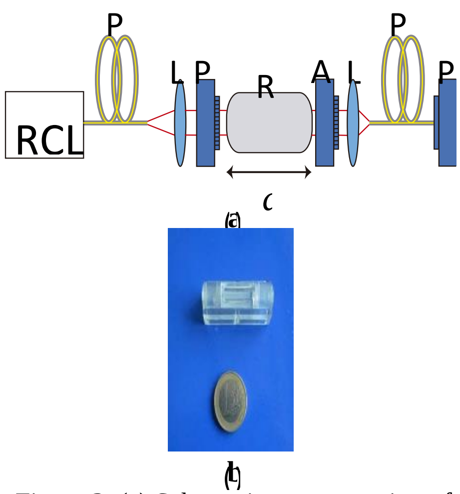

Figure 3. (a) Schematic representation of the optical head of the low-cost current sensor. L1, L2: collimating lenses; POL: polarizer; ROD: magnetooptical rod; ANA: analyser; PD: optical photodetector. (b) Close-up view of the magnetooptical rod.

Light is transmitted from the mild supply to the sensor optical head through a quick segment of POF. The POFs used are polymethylmethacrylate (PMMA) fibres with a center diameter of 980 μm and a numerical aperture of zero.5. The unpolarized mild from the RCLED passes via the collimator. The collimator transforms the divergent mild right into a parallel beam earlier than attaining the linear polarizer-sheet. We use a collimator to lessen extra losses alongside the mild direction. When the mild passes via the SF2 rod, the aircraft of polarization rotates in keeping with the depth of the magnetic discipline. After passing via the analyser, any other collimator focuses mild into any other segment of POF, which transmits the modulated depth of mild to the detector. One of the blessings of this set-up is that the optical element may be located near sufficient to the modern-day conductor without stressful the distribution of the magnetic discipline and, therefore, the accuracy of the modern-day measurement. In the simple scheme of the polarimetric readout (Figure 1), the major axes of the polarizer and the analyser are orientated at 45° with recognize to every different if you want to attain a terrific linearity of the sensor reaction. Thus, the output irradiance isbecause of this that that the AC factor of the irradiance IAC stages from zero to I0/2 whilst the electrical modern-day is going from zero to round 340,000 A for the SF2 glass. When the electrical modern-day is going from zero to 800 A, we are able to attain a minimal strength lack of at the least 11. fifty-nine dB (at 800 A), which units the most output strength. The output photodiode modern-day of the receiver, that's immediately proportional to the optical strength attaining the PIN photodiode, is same to: in which is the responsibity of the transceiver (□ ~ zero. three for the FC300T transceiver). Therefore, with the aid of using measuring the photodiode modern-day, the electrical modern-day via a strength transmission line may be found. The uncertainties associated with versions of the optical direction can without problems be removed with the aid of using normalizing the AC output modern-day iAC photodiode with the DC output modern-day iDC photodiode. This way, the sensor reaction relies upon neither at the mild strength nor at the misalignment of the optical components.

V. ELECTRONICS

Figure four indicates the digital set-up for the purchase of the modern sensor reaction signals. The photodiode converts the optical sign to an electric powered modern. This electric powered sign includes additives (refering lower back to Equation (8)): an alternating modern (AC) aspect, because of the impact of magnetic discipline withinside the rod, and a right away modern (DC) aspect, because of the mild rectification. Both additives are amplified the usage of a low enter bias modern operational amplifier. The benefit of the amplifier is identical to the fee of the resistance R. R ought to be of a completely excessive fee (>>10 kΩ) to deal with the electrical sign to the analog to virtual converter (ADC) while the modern thru the strength transmission line is the maximum (i.e., 800 A). The VREF voltage is used to compensate de DC aspect of the mild with a purpose to accommodate the electrical sign to the ADC.

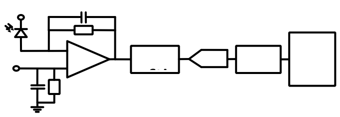

Figure 4. Electronic set-up for the acquisition of the optical current sensor signals.

The amplified sign is then filtered to keep away from aliasing effects. Afterwards, the sign is sampled the use of a quick sixteen bits ADC. The samples are processed the use of a virtual sign processing set of rules on a FPGA device, which calculates for every cycle the 50 Hz (AC component) and zero Hz (DC component) discrete Fourier transform (DFT) of the cutting-edge sign [25]. The DFT values are saved in a reminiscence which is out there from a laptop. Figure five suggests the custom hardware advanced for the purchase of the low-value optical cutting-edge sensor alerts (the hardware consists of the Firecomms FC300T fibre optic transceiver). Due to the very vulnerable optical alerts obtained for low currents throughout the conductor, sign integrity withinside the hardware layout has been of very excessive importance [26]. The custom digital hardware is modular and it could effortlessly be utilized in a rack collectively with different current sensors (resistive sensors, toroidal sensors, etc.) that degree different parameters of the electrical transmissionlines

Figure 5. Custom electronic hardware for the acquisition of the current sensor signals.

VI. EXPERIMENTALSECTION

Characterization of the Optical Head Optical extra losses withinside the optical head rely upon each the fine of the additives and the geometry of the design. We have calculated those extra losses taking into consideration emitter-POF coupling losses, POF transmission losses, Fresnel reflections at any air-plastic or vice versa interfaces, collimators and polarizers absorption losses, and, finally, POF-receiver coupling losses. We have additionally covered losses because of the misalignment of the optical additives (POF-collimator-rod), that's crucial to couple the mild into the SF2 rod and to couple it again into the receiving fibre. We have in comparison this calculus with a right away size of the extra losses of the optical head. To accomplish this undertaking, we've got measured the optical electricity throughout the optical head and thru a bit of POF. Excess losses are simply the mild electricity difference. By including some of these contributions we've got anticipated a theoretical cost of 20 dB, while the experimental measurements ended in a cost of sixteen dB. The small confrontation is because of the conservative man or woman of the theoretical calculus of the reassets of loss, seeing that we've got assumed the worst-case state of affairs for the mechanical tolerances.

VII. RESULTS

Laboratory checks had been executed the usage of a conductor with a diameter of five cm. Figure 6 shows the experimental set-up of the low-price optical cutting-edge sensor and the electronics defined in preceding sections. The optical head of the cutting-edge sensor became connected to the conductor the usage of a dual-aspect adhesive tape. Different cutting-edge values had been injected to the conductor the usage of a CPC-a hundred general checking out tool through Omicron [27]. The CPC-a hundred can generate cutting-edge values starting from zero A to 800 A. The checking out tool became linked in collection to the conductor the usage of manner furnished through the manufacturer. Care became taken to vicinity the sensor some distance sufficient from the CPC-a hundred to lessen the 50 Hz interference from the checking out tool.

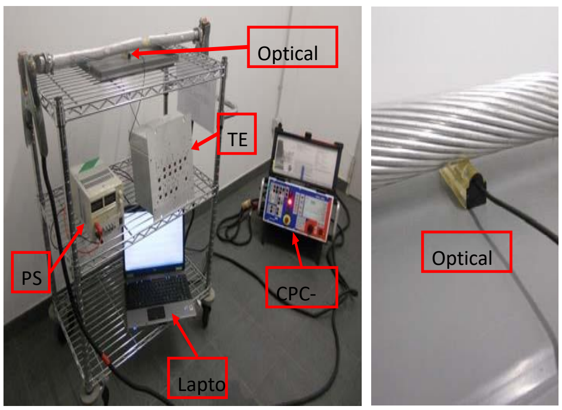

Figure 6. Test set-up of the low-cost optical current sensor (Left). Optical head detail (Right). TE: test equipment, including the electronic hardware for the acquisition inside. PS: power supply. Laptop: used to acquire all the data. Optical head: optical head of the current sensor.

The low-value optical contemporary sensor become examined for exceptional contemporary values, starting from zero A as much as 800 A. For every contemporary value, 256 samples of DFT have been saved in reminiscence and the mathematics imply become calculated. The DFT consequences have been normalized to the DC factor values, with the intention to cancel uncertainties because of versions withinside the optical course or mild fluctuations. For instance, Figure 7 indicates the illustration of the sign obtained for I = 400.

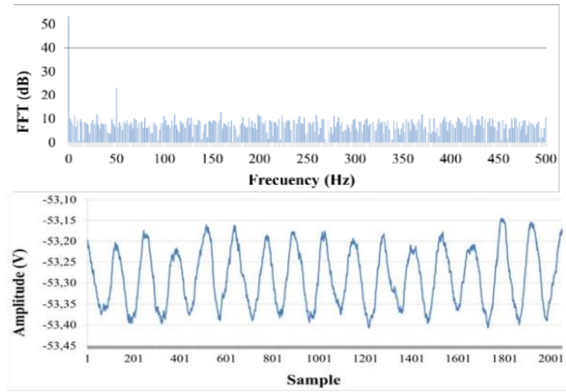

Figure 7. Optical signal received after amplification for I = 400 A (Above). DFT of the optical signal from 0 to 500 Hz (Below).

We have plotted the 50 Hz issue of the DFT as a characteristic of the modern-day in Figure 8. In each instances the measurements had been repeated 5 times, and the imply price and its least imply squared curve-suit changed into calculated. It is obvious from the imply price (pink squared curve withinside the first case and blue squared curve withinside the 2nd case) that the reaction of the modern-day sensor famous a excessive diploma of modern-day linearity, a truth assessed through the R2 coefficient derived from the precise process (R2 = 0.99986). The nice suit is represented through a pink line in Figure 8a and through a blue line in Figure 8b. The vertical blunders bars denote the uncertainties related to every modern-day measurement.

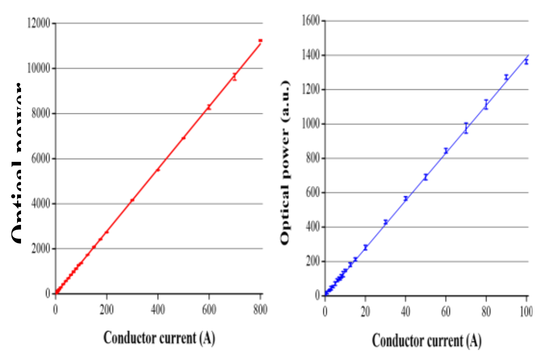

Figure 8. (a) 50 Hz component of the normalized DFT from I = 0 A to I = 800 A.
(b) 50 Hz component of the normalized DFT from I = 0 A to I = 100 A.

For cutting-edge values decrease than 20 A, the reaction of the sensor is tormented by the noise of the acquired optical sign and the ground noise of the purchase system.

For cutting-edge values more than 30 A, the dimension uncertainty is much less than 5%. In order to degree with an mistakess decrease than 1%, the cutting-edge have to be more than a hundred seventy-five A. This improves the outcomes acquired via way of means of different authors with glasses composed of oxides of heavy metals in addition to telluric glass [28] or optical fibers doped with CdSe quantum dots [29], whose errors, withinside the identical cutting-edge variety, are round 20%. However, they're worse than different optical cutting-edge sensors primarily based totally on unmarried mode fibers in an interferometric configuration. Accuracy and repeatability of those sensors are within ±0.1% over a extensive variety of cutting-edge and temperatures [30,31]. Their counterpart is their plenty better rate and top-notch complexity.

On the alternative hand a toroidal cutting-edge transformer with ferromagnetic core, conventionally utilized in area programs for cutting-edge dimension, has an mistakess of much less than 1% for cutting-edge values more than forty A. Therefore, the accuracy of the low-price cutting-edge sensor is barely decrease than that of traditional cutting-edge sensors. Nevertheless, the accuracy of our cutting-edge sensor can be stepped forward in destiny prototypes via way of means of keeping apart the DC and AC additives earlier than analog to virtual conversion or via way of means of enhancing the optical head of the cutting-edge sensor the usage of higher magneto-optical rods (growing the rate goal). The mechanical traits of the optical head may also be stepped forward to lessen sign loss because of optical misalignment. All in all, we accept as true with that our cutting-edge sensor prototype is correct sufficient for programs wherein the precision at low cutting-edge values isn't always critical, together with fault discover programs.

CONCLUSION

A new low-price optical modern sensor has been advanced. The sensing principle, its optical and digital design, in addition to its characterization had been described. The overall performance of the prototype turned into examined experimentally. Our modern sensor is low price, with proper reliability, and has a linear reaction from zero to 800 A with an accuracy over 1% for modern values over a hundred seventy-five A. Additionally, the modular electronics advanced for the sensor can without problems be geared up in a rack collectively with different present sensors measuring different parameters of the electrical transmission lines. Although there may be a huge variety of packages for this sensor, it's going to in particular used to display currents each on overhead and underground electric distribution lines.

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