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Design of Modern Optical Fiber Current Transformer

SULIEMAN EDOUD
Lecturer, Dept. of Electrical and Electronic Engineering
Nyala University
YOUSIF H.A. RAHIM
Professor, Dept. of Electrical and Computer Engineering
Karary University
ABDELAZIZ Y. M. ABBAS
Assoc. Professor, Dept. of Electrical and Nuclear Engineering
Sudan Univ. of Science and Technology,
GIDDANI KALCON
Assoc. Professor, Dept. of Electrical and Nuclear Engineering
Sudan Univ. of Science and Technology

Abstract:

This paper describes the design of an optical fiber current transformer (OFCT) based on magneto-optic Faraday Effect. OFCT is designed using helium-neon laser (with wavelength of 632.8 nm and power of 1 mW) as light source, single mode fiber based sensing element and photomultiplier as detector.

This OFCT is presently designed to cover current in the range of (20 A to 450 A). Preliminary experimental results for an OFCT are presented. The OFCT gave good results under various electrical current supply values, and responded in a linear behavior to an applied electric current. The OFCT achieves highly accuracy over a wide dynamic range of currents. The results obtained proved that the OFCT can be used in high voltage substations due to their superior accuracy, bandwidth, dynamic range and inherent isolation.

Key words: optical fiber; Faraday effect; optical fiber current transformer; current measurement.

I. INTRODUCTION

The dramatically development and revaluation occurred in last decade in lasers and semiconductor optoelectronic result in introducing new generation of electronic and electrical measurement devices with high accuracy and quality.

Conventional electromagnetic current transformer (CT) is an important measurement device used in electrical power system. CT is designed to provide a current in its secondary coil that is proportional to the current flowing in its primary side [1]. It has multiple usage such as measuring the current in high voltage transmission lines, protection of electrical devices in substation and generation plants. One of major problems of conventional CT is tendency of to saturation due to a large magnetic field caused by high fault currents [2]. The saturation of the iron core prevents the transformer from accurately represent the primary current in the current transformer secondary, and therefore distorts current measurement [3].

An optical fiber current Transformer (OFCT) is developed and used in power system protection and monitoring similarly functions like conventional current transformer. Optical current Transformers are achieving increased acceptance and usage compare to conventional CT in high voltage substations and generation plant.

The most significant advantages of OFCT are high accuracy and sensitivity, large dynamic range, fast response, immunity to electromagnetic interference and potential low cost. Also, OFCT used in explosive environments where electric sparks must be prevented because the measuring process does not involve the conduction of an electric current, it is very suitable to measure current in hazardous environments[4]-[6]. The intrinsic insulation of the optical fiber is a key feature for high voltage installations. It is possible to use it without any risk of discharge with the ground. In addition, OFCT has wide bandwidth making the observations of harmonics and transients easier. In addition, OFCT shows no saturation effects and can effectively replace conventional iron core transformers in specific areas with the very high currents that occur during a fault on the power system. Finally, optical fiber is small size, therefore the design of lightweight and compact sensors is easy. Its installation is moreover quick, simple and can be done without interrupting [7].

Fiber current transformers based on the Faraday effect and are particularly attractive because they have better optical integration than other OCTs such as bulk-glass current transformers or space coupling OCTs [8].

The Faraday Effect states that, the plane of polarization of linearly polarized light propagating in a material, which exhibits the magneto-optic effect, and which is placed in a magnetic field undergoes a rotation through an angle which is proportional to the magnetic field component parallel to the direction of propagation.

In this paper, modern OFCT is developed to measure the current flowing in transmission line. In addition, both theoretically and experimentally techniques of OFCT based on the Faraday Effect are compared.

II. OPERATION PRINCIPLE OF OPTICAL FIBER CURRENT TRANSFORMER

Instrument transformers are used with measuring and protective equipment in order to monitor electrical parameters such as current and voltage or to use these parameters to activate protection schemes. The general structure of an optical Instrument Transformer system is shown in figure 1. It consists of an optical source, optical fiber, sensing or modulator element, an optical detector and signal processing electronics.

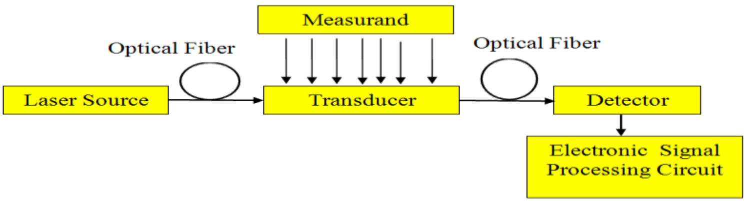

Figure 1. Basic components of an optical fiber Instrument Transformer.

The operation of Optical fiber current transformer is based on Faraday Effect. The Faraday Effect, sometime referred to as Faraday rotation, is based on interaction between the external magnetic field and the oscillation of the electrons in the medium. The angle of rotation of linearly polarized light is proportional to the strength of the magnetic field and the cosine of the angle between the field and the propagation direction of the light wave. This rotation can be expressed mathematically by (1).

$$\varphi = \int_L V\vec{B}.dl \qquad (1)$$

where φ is the angle of state of polarization, $\boldsymbol{V}$ is the material Verdet constant, which is both dispersive and temperature dependent [9], $\boldsymbol{B}$ is the magnetic flux density vector and dl is the differential vector along the direction of propagation. Faraday rotation is directly proportional to the Verdet constant. The sensitivity of Optical fiber CTs depend on Verdet constant which indicates the rotation angle of the polarization per unit magnetic field per unit propagation length. The Verdet constant is an optical constant that describes the strength of the Faraday

Figure 2 illustrates the polarization rotation due to a parallel external magnetic field on a magneto-optical material, such as, glass.

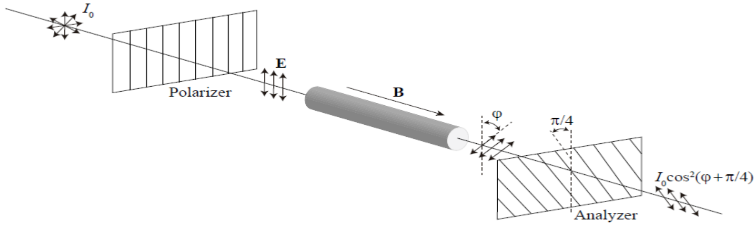

Figure 2 Faraday Effect in Linearly Polarized Light.

The Verdet constant characterizes the capability of a transparent medium to rotating the sensitivity to magnetic fields tend to have the greatest temperature dependence polarization plane in a magnetic field. The Verdet constant is also wavelength dependent and will be affected by temperature. The Verdet constant is determined as in (2).

$$V = -\frac{e\lambda}{2mc}\left(\frac{d\mathrm{n}}{d\lambda}\right) \tag{2}$$

where, $\left(\frac{d\mathrm{n}}{d\lambda}\right)$ is the dispersion of intrinsic index which is indicates that the Verdet constant is linearly proportional to the dispersion of the material and the *e* and *m* are charge and mass of an electron respectively , *c* is the speed of light in vacuum.

The refractive index (n) of the medium depends on wavelength (λ) according to Cauchy's equation:

$$n = a + \left(\frac{b}{\lambda^2}\right) \tag{3}$$

Where *a* and *b* are constants. Combining the equation (2) and (3.), yield the verdet constant as a function of wavelength is given by (3.18).

$$V(\lambda) = \frac{K_1}{\lambda^2} \tag{4}$$

Where, $K_1 = eb/mc$ is a constant.

The operation of optical current sensors based on rotation of polarization direction by the magnetic field paralleling with the direction of the optical beams. When the optical path is closed, the rotation angle of the polarization plane is in proportion to the product of the Verdet constant of the sensing materials and the current generating the magnetic field. For Optical Fiber Current Transformer, a magnetic field will be built up round the current-carrying Conductor, satisfying Ampere's circuital law. Therefore, the rotation angle φ_F in the fiber is expressed as in (5).

$$\varphi_F = \oint Hdl = N_F V I_{elec} \qquad (5)$$

Where, N_F the number of turns of sensing optical fiber loop is, $I_{elec}$is the electrical current in conductor.

The sensitivity of OFCTs depend on Verdet constant, which indicates the rotation angle of the polarization per unit magnetic field per unit propagation length. Compared with the bulk devices, the Verdet constant of optical fibers is quite small, but the optical path length can be increased to compensate for it by winding the fiber around a current conducting element a large number of turns [10].

III. OPTICAL FIBER CURRENT TRANSFORMER CONFIGURATIONS

Several different configurations have been proposed in open literature in order to detect the Faraday Effect. The main detection schemes are summarized as follow:

1. Basic Polarimetric Detection Configuration

In this configuration two polarizers are used, one at the input of the sensor act as polarizer and the other at the output as analyzer as shown in Figure 3. The angle offset between the transmission axes of the polarizer and analyzer is aligned at

45° by a polarization controller. The intensity of the output light is given by (6).

$$I_{out} = I_{P1}.\cos^2(\varphi_F) \quad (6)$$

where, I_{P1} is the light intensity after the first polarizer and where φ_F is the angle of state of polarization is the relative angle between the transmission axes of the polarizers.

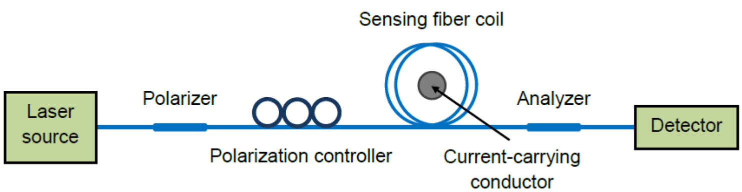

Figure 3 Polarimetric Detection scheme.

The basic polarimeter would require calibration when the sensing fiber coil contains non-negligible linear birefringence [11]. The polarized light propagates along both axes of the birefringent fiber due to a possible interface angle-offset and Faraday rotation. Unless the transmission axes of the polarizer is aligned at 45° to that of the birefringent fiber axes such that one of the fiber axes is aligned with that of the analyzer, the two beams with different phase delays may produce unwanted interference effects at the analyzer.

2. Dual Quadrature Detection Configuration

In Dual Quadrature configuration which is presented in Figure 4, linearly polarized light propagates through the fiber as sensor element. While propagating through the fiber coil, the plane of polarization of the light rotates in the presence of a magnetic field. At the output end of the polarizer there is beam splitter, that separates two orthogonal polarizations in two distinct outputs, S_1 and S_2. These two signals are detected by two independent photodetectors and processed by an analog circuit that computes the output signal ***S*** as:

$$S = \frac{S_1 - S_2}{S_1 + S_2} = sin(4\varphi_F) \quad (7)$$

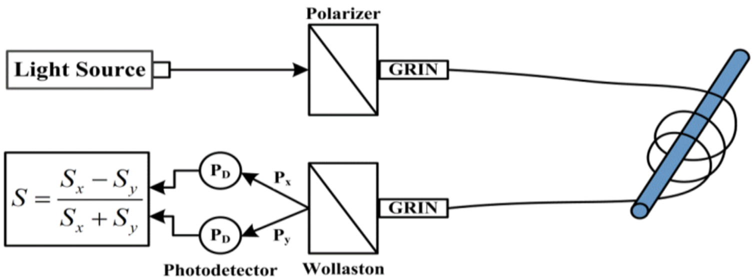

Figure 4 Schematic of Dual Quadrature polarimetric

3. Interferometric Detection Schemes

In the interferometric detection scheme the rotation of the plane of polarization analyzed in terms of circular polarization, corresponding to a phase difference between the two circular orthogonal mode. Figure 5 shows a Sagnac interferometer configured for the Faraday Effect, which is commonly used in gyroscopes and it is sensitive to non-reciprocal effects [11]. This interferometer is interrogated by using a heterodyne detection scheme.

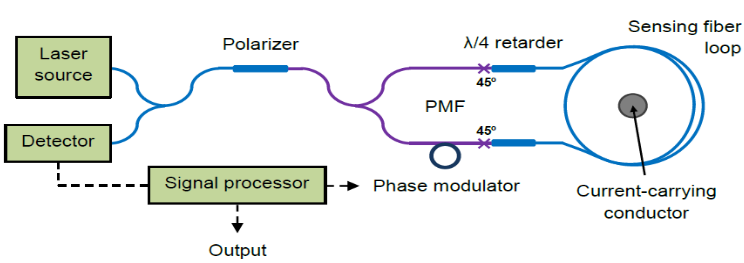

Figure 5 Sagnac loop interferometer current transformer.

In this particular application, light from an optical broadband source, is linearly polarized with a fiber polarizer and is injected into the Sagnac loop with crossed λ/4-wave plates mounted at an angle of 45° and −45° relative to the plane of polarization of the linearly polarized inputs, for the upper and lower plate, respectively. In this configuration each of the counter propagating waves are converted to orthogonal circular states. These two counter propagating waves travel the Sagnac loop with different velocities, due to the external magnetic field induced circular birefringence. After crossing the loop, they are converted again into linear polarization modes and interfere after crossing the output linear polarizer. Finally, the two beams combine in the Polarizer Maintaining Fiber PMF to produce an optical power modulation at the polarizer.

$$P = \frac{P_o}{2}.(1 + \cos(\Delta\varphi_F)) \quad (8)$$

IV. System components and Experimental Setup

In this paper, Dual Quadrature Scheme is used to analysis the operation of OFCT As shown in Figure 6. Our experimental setup consists of five main elements: Laser, Polarizer, sensing head, Photomultiplier and Electrical current source. The system components are described as follow:

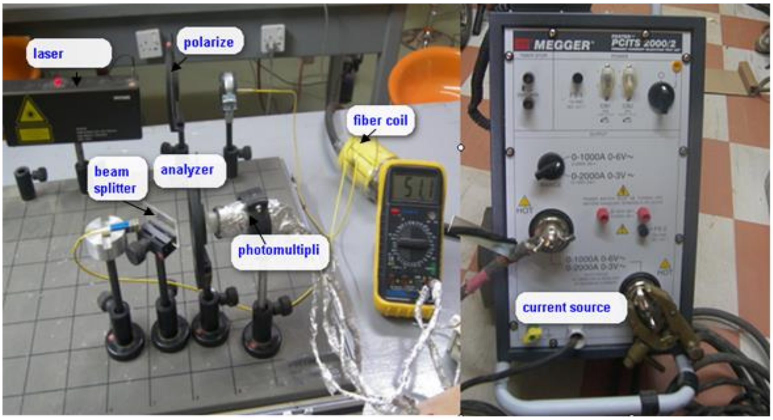

Figure 6. Experimental setup

1. **Laser light Source:** Helium Neon laser (PHYWE) of 1 mW output of laser source having wavelength 632.8 nm was used in this work. The Helium Neon laser used because of the following reasons:
   - It has low beam divergence (high collimation) provides easy coupling the beam in single mode optical fiber.
   - It have suitable wavelength (632.8 nm) to provide high verdet constant allowed strong Faraday Effect.
2. **Polarizers:** Three polarizer were used one as a polarizer to polarize incident light beam (linear polarization) aligned in front of the sensing element (optical fiber), and the second and third are used as analyzers behind the sensing element.
3. **Optical Fiber and its Accessories:** Single Mode Fiber with a relatively narrow diameter, through which only one mode will propagate. The single mode optical fiber was winded around the current carrier about 36 turn with diameter of 8 cm. It has a core /cladding diameter 9/125 µm stamped on the yellow cable jacket, and terminated with connectors FC and SC. SC- a push/pull type connector. This connector has emerged as one of the most popular styles. Single mode is used to maintain state of polarization and it is used as a sensing element.
4. **Beam splitter:** Non-Polarizing Beam splitters are available in two forms: plates and cubes. The low polarization dependence of the metallic-dielectric coating allows the transmission and reflection for S- and P-polarization states to be within 3% of each other. This means that they will not change the state of polarization of the incident beam.
5. **Photomultiplier:** The photomultiplier is one of the most important single element photodetector. One way to increase the sensitivity is to add amplification between the photocathode and anode. Incident photons eject electrons from photocathode, as the electrons move from photocathode

to anode; they strike a series of secondary electrodes called dynodes, which are held at potentials intermediate between the cathode and anode. When an electron strikes a dynode, it ejects a number of additional electrons, each of which is then accelerated to collide with the next dynode. The result is an avalanche process, with the number of electrons increasing exponentially. The photomultiplier used was The H6780 photosensor.

6. **Electrical Current Source:** The electrical current source used was MEGGER PCITS2000/2 Primary Current Injection Test Set. The maximum output current is 2000 A a.c. at line frequency.

V. EXPERIMENTAL TESTS AND RESULTS ANALYSIS

This configuration allows measuring electrical current that flows through a conductor by analyzing the photodetectors optical power behavior when the current value is changed. The performance of the model is evaluated by varying the output of the current source from 20 A to 450 A and measure the angle of polarization and calculate the input current.

When polarized light passes through the optical fiber coil, it experiences a shift in its plane of polarization, which is proportional to the magnetic field induced by the current in the conductor. The polarization rotating angle caused by the magnetic field is related to the optical power that detected by photomultipliers.

Photomultipliers outputs must be normalized to obtained accurate electric current pass through conductor. Since, the differences normalized Sum operation (Δ/Σ) allows eliminating sources of noise common into output signals. Therefore, the angle of polarization rotation is reconstructed by (9).

$$\varphi_F(V_X, V_Y) = \frac{1}{2}\arcsin\left(\frac{V_X - V_Y}{V_X + V_Y}\right) \quad (9)$$

Accordingly, the electrical current can be obtained in (10).

$$I_{elec} = \frac{1}{2VN} \arcsin\left(\frac{V_X - V_Y}{V_X + V_Y}\right) \quad (10)$$

One major error source is noisy input signals V_X and V_Y. Hence, a sensitivity analysis is required to estimate the impact of noisy signals on φ_F.

An optical polarizer beam splitter is used to split a beam of light into two orthogonal components depend on polarization state. These components are represent such a beam splitter that transmit radiation polarized type "P" which its electric field intensity vector is in parallel with the plane of incidence and will reflect “S” polarized radiation which its electric field intensity vector is perpendicular to the plane of incidence. In order to obtain maximum sensitivity the polarizer must be attuned at 45° clockwise with respect to X-axis of the polarized input ray, the intensity components of will be expressed as (11).

$$V_X = \frac{1}{4} E_o^2 \cos(45^0 + \varphi_F) \quad (11a)$$

$$V_Y = \frac{1}{4} E_o^2 \cos(45^0 - \varphi_F) \quad (11b)$$

If both reflection and transmission output change is recorded synchronously, after heterodyne data processing is given in (7). [49].therefore the electrical current can be calculated by (10). Table .1 shows the obtained results during the experiment for input current up to 450 A.

Table 1. The result of the Dual Quadrature Polarimetric Configuration

Measured current[A]	V_X [V]	V_Y [V]	$\frac{V_X - V_Y}{V_X + V_Y}$	φ_F [degree]	calculated current[A]
20	5.38	5.34	0.003731343	0.21389916	21.22
40	5.39	5.32	0.006535948	0.37467483	37.17
60	5.41	5.3	0.010270775	0.58878089	58.41
80	5.43	5.28	0.014005602	0.80289517	79.65
100	5.45	5.27	0.016791045	0.9625892	95.49

120	5.47	5.24	0.021475257	1.23116032	122.13
140	5.48	5.22	0.024299065	1.39307717	138.20
160	5.5	5.2	0.028037383	1.60744917	159.46
180	5.52	5.18	0.031775701	1.82184367	180.73
200	5.54	5.16	0.035514019	2.03626366	202.01
250	5.59	5.11	0.044859813	2.57244493	255.20
300	5.63	5.08	0.051353875	2.94514817	292.17
350	5.68	5.03	0.060690943	3.48123801	345.36
400	5.72	4.98	0.069158879	3.96768887	393.61
450	5.78	4.91	0.081384471	4.67051739	463.34

Based on the experiment results shown in Table.1, the graphical relation between the measured and calculated input current and angle of state of polarization are plotted as shown in Figure. 8, 9, and 10, show linear relationship between the input current and the angle of polarization state rotation. Therefore, the angle of polarization will reflect the input current value accurately if the proportional constant is determined. In addition, it is clear that the OFCT is linear without saturation effect.

It is possible to notice the dependence between Photomultipliers outputs and angle of light state of polarization φ_F. Therefore, an angle of polarization rotation change due to stress bend or any external disturbance may mask the φ_F change due solely to the current change.

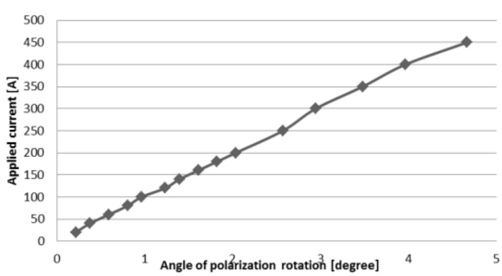

Figure 8 Applied current Versus Angle of polarization state rotation

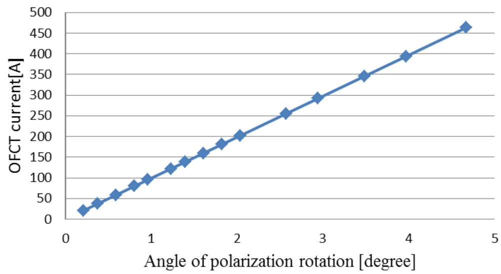

Figure 9 the OFCT current versus the angle of polarization state rotation

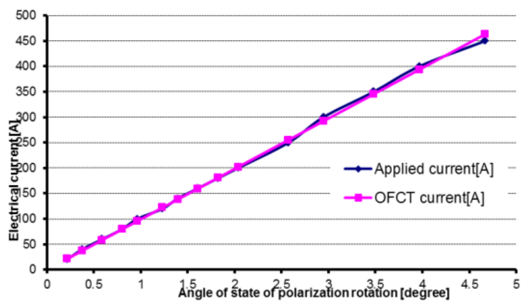

Figure 10 the comparison of Applied and measured current

The current measured by OFCT is similar to electrical current applied with small differences. These differences referred to: the resolution of digital multimeter, the polarizers axis shifting, state of polarization rotating detection system and the fiber used.

The OFCTr configuration gave good results under various electrical current supply values. The technique presented in this configuration provides a suitable configuration for the OFCT of electrical current measurements. Used of beam splitter has positive effecting in the OFCT performance and reduce the error, but show slight error in high values of current.

VI. CONCLUSION

The Measuring of high electrical current in normal or fault condition is more accurate when using OFCT without any error due to saturation effect. This is very important especially when OFCT used with protection system.

Compared to conventional current transformer the OFCT offers a number of inherent advantages with regard to performance and ease of handling. They offer better accuracy, and wider bandwidth in comparison to conventional CTs. Many problems of their conventional counterparts are inexistent such as magnetic saturation or danger of catastrophic failure.

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