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Optical Technology in Current Measurements as a Substitute to Inductive and Capacitive Measurement Transformers: A Case for the Nigerian Electricity Industry

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ABSTRACT : *Electric utilities have started assessing optical sensors to measure voltage and current as recent researches suggest. These devices are showing their worth, particularly in situations where enhanced safety, modification and precise measurement over a larger dynamic range are the primary concerns. Using cutting edge laser technology, optically powered current transformers are used to detect currents and transfer data from high voltage systems to ground potential. The concept of isolating the current transformers from ground potential using fiber optic cables is one of this technology's foundations. The optically powered current transformer (OPCT) technology, which measures currents for metering or protection in high voltage applications, is defined and explained in this study. They are ideal for the cutting-edge protective relay and meter functionality as well as the digital communications adaptability seen in present substations.*
KEYWORDS- *Fiber Optic Current Sensor, Optical Sensor, Fiber optic cable. OPDL Remote Board,*

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I. INTRODUCTION

Over the last two decades, researchers have shifted their focus toward optical current sensors as cutting-edge high voltage measurement tools poised to replace traditional iron-core current transformers in the emerging smart grid power sector. Optical current sensors are gaining prominence due to their inherent advantages: they are non-conductive and lightweight, simplifying insulation and mounting in design considerations [1]. Moreover, optical sensors exhibit notable benefits such as the absence of hysteresis and a substantially wider dynamic range and frequency response compared to their iron-core counterparts [2].

A prevalent characteristic of many optical current sensors is their operation based on the Faraday Effect. In this mechanism, the flow of electric current within a conductor generates a magnetic field, which, in turn, causes a rotation in the plane of polarization of light circulating around the conductor [3]. Ampere's law assures that "if the light maintains uniform sensitivity to the magnetic field along its sensing path, forming a closed loop, the cumulative rotation of the light's polarization plane directly correlates with the current within the enclosed wire" [4][5]. Notably, these sensors remain impervious to externally induced magnetic fields, including those originating from neighboring wires. Consequently, measuring the rotation in polarization state using Jones Matrices provides an accurate measure of the desired current [6].

In order to measure currents in Series Capacitor installations, this technology initially appeared about decade ago. Following this, it has been used in High Voltage Direct Current Systems (HVDC) as well as Series Capacitor and Thyristor Controlled Series Capacitor installations (SCTSC) [7]. These SCTSC and HVDC systems benefit significantly from the high availability and reliability enabled by optically powered current transformer technology [8]. Further to the continued integration of optically powered technology into the grid system, it has yielded cost-effective and robust metering and protection current transformers, effectively eliminating the known environmental issues associated with oil or SF6-gas filled alternatives which this paper seek to examined.

II. OVERVIEW OF LITERATURE

Uswa (2014) states that the optical current transformer (OCT) uses state-of-the-art laser technology to measure currents and transmit data from high voltage systems to ground potential. Using fiber optic cables to isolate current transformers from ground potentials is the basis for this technology [5]. The advantages of the optically powered scheme over the conventional, high voltage, free standing magnetic current transformer (CT) consist of an environmentally friendly, compact and non-seismic essential composite signal column in addition to the tried-and-true, conventional, low voltage rated 'dry type' CT technology [1].

1 Fiber Optic Current Sensor

As seen in figure 1, the widely recognized FOCS scheme is based on the Faraday effect, which occurs in a unique spun fiber wound around a current lead and affects a polarized light phase. These FOCS are intended for voltage classes of 110–220 kV and higher, though they are also practicable at smaller voltages [9]. According to Wang's summary [10], there are a few benefits to using a fiber optic current sensor over a traditional current transformer. For high voltage applications, the optical fibers intrinsic insulation is essential. It can be used without running the risk of discharge into the earth. They also provide complete immunity to external magnetic fields and have a broad bandwidth, which enables the study of transients and harmonics. Lastly, because optical fiber is so tiny, it is simple to construct light, compact sensors with performances that are on par with those of traditional sensors, which are also large, heavy, and bulky. Furthermore, it may be installed quickly, easily, and without stopping the electric circuit in order to measure [11].

Prototypes for commercial optical current sensors are primarily being developed in two flavors: bulk and fiber polarimetric. High Verdet constant crystals are used to realize bulk current sensors, which have excellent sensitivity. Although optical fibers have a lower Verdet constant, their sensitivity is improved by winding the fiber around the conductor many times. The polarimetric method measures the rotation of a linear polarization, while the non-reciprocal phase shift is measured using an interferometric configuration with a Sagnac interferometer
[10].

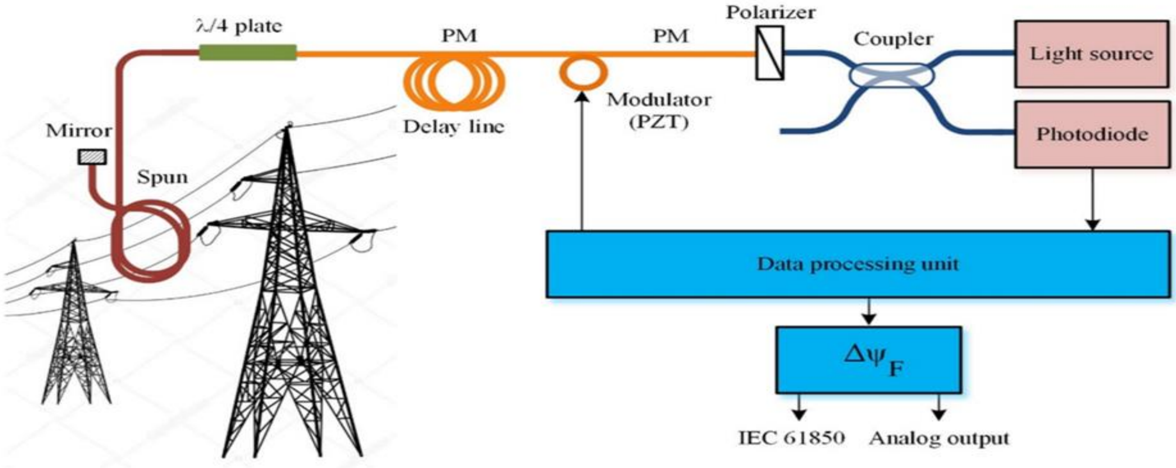

Figure 1: Optical scheme of fiber optic current sensor (FOCS) [9].

The following elements make up the FOCS optical path: Light origin, A polarization-maintaining optical fiber wound around a piezoelectric transducer (PZT) serves as the phase modulator (PM), Line of fiber delay, Plate with quarter wave fiber, Sensor component composed of twisted optical fiber, Mirror, Sharpener/ Polarizer, Photodiode and Unit for processing data.

Using a PZT resonant modulator and a harmonic signal with the dependency $\Delta\psi M(t)=\psi m.\cos(2\pi f M t)$, additional phase modulation of light is achieved in FOCS. The sole piezoceramic resonance frequency that can be used for modulation (FM=40.1 kHz) is restricted by the employment of such a modulator in the circuit [12]. Digital technology is used for phase detection. This is accomplished by extracting the first and second harmonics of the modulation frequency from the photodetector-recorded signal and analyzing their ratio [9]. It is a widely recognized technique in fiber optic gyroscopic.

2. The Optical Current Transformer Arrangements

Fig. 2 illustrates the total OCT functional blocks. A burden resister is connected to the CT. The CT sensor is a low voltage rated CT, but the overall resistance of the secondary circuit, or load, is the result of adding the resistances of the relay/meter, connecting wires (lead resistance), and the CT secondary winding. VA is used to express the current transformer's burden. When CT is employed for protection or measurement, the entire VA burden should be taken into account [13]. Both have the necessary certifications for the metering application and intended protection. The Optically Powered Data Link (OPDL), the central component of this technology, receives the voltage output from this sensor head. Two links can be formed from the fibers that link the OPDL units to the ground and the HV remotely. The first is the fiber-incorporated composite insulator, which is attached to the

OPDL remote unit at the high voltage side. The ground side of the signal column, which is linked to the fiber cable that is connected to the control, makes up the second link. The signal output for the metering and monitoring apparatus, as well as the protective relays, is supplied by the receiving unit located in the current control enclosure. This system is made up of four fundamental components as indicated in fig. 3.

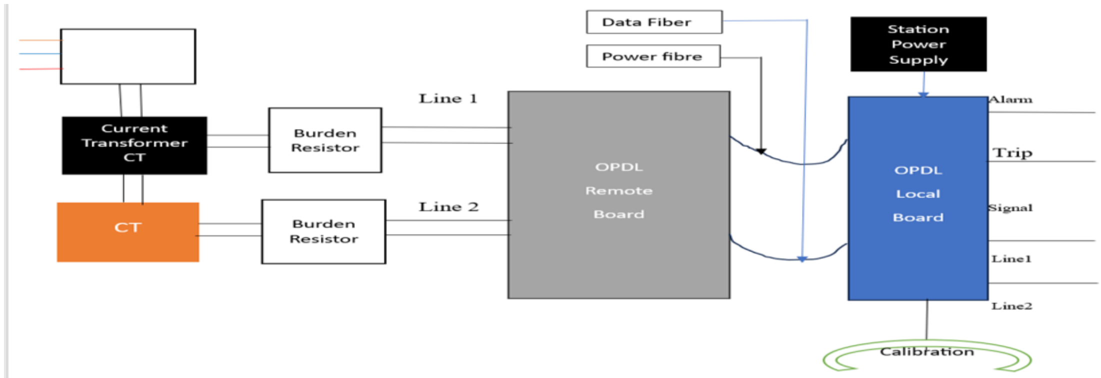

Figure 2: Block system of Optical current transformer (OCT)

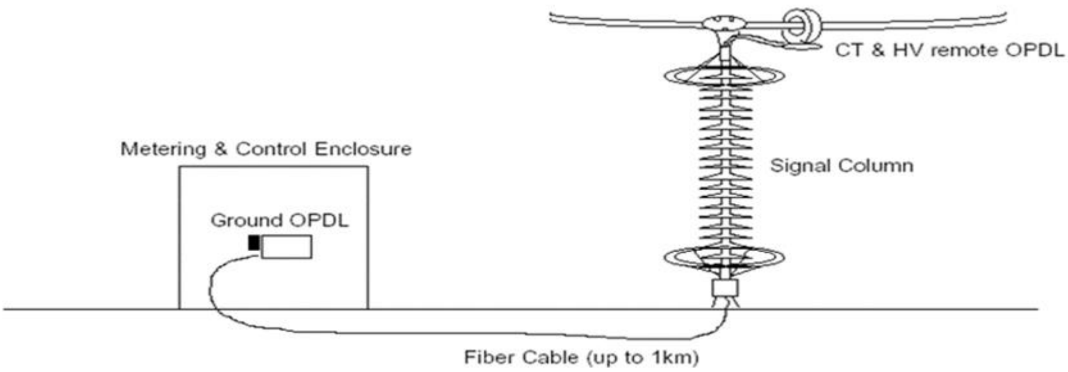

Figure 3. Optically powered current transformer system.

3. The Remote And Internal Configuration Of The Optically Powered Data Link (OPDL)

The substation control room or an existing control enclosure serves as the platform for the local unit of the OPDL system, while the distant unit operates at high voltage potential. The laser, the laser driver, and the circuitry for data recovery are all housed in this device. A maximum of 1.5 Watts of optical power can be coupled into the power link fiber by the laser technology utilized for this application. As their mean time between failure (MTBF) is greater than 100,000 hours, these lasers are not expected to be extremely dependable or have a lengthy lifespan. Every essential OCT function is overseen by a self-check function. Long before the laser's lifespan is up, an alarm will sound to indicate that maintenance is needed. If a malfunction is detected by the system, a trip signal will be triggered.

This machine can give a digital serial output of +/- 10 Volts (full scale) or a current loop of 1 amp (nominal) @ maximum 20 or 40 VA, depending on the metering or relay scheme [14]. Any station power supply may readily provide the power needed to operate this machine. Two optical fibers—a data link and a power fiber—connect the OPDL local ground unit to the high voltage system's remote electronic board. The remote unit transforms the voltage drop across the CT burden resistor into digital signals and is protected from any electromagnetic magnetic interference (EMI) or RFI, which is radio frequency noise. With a conversion efficiency of up to 45%, the photovoltaic power converter coupled to the laser via one of the fiber optic cables provides the electricity needed to run this device. Two analog-digital (A/D) channels, each with a 45 kHz sampling rate and a 25 kHz bandwidth (240 harmonics @ 50 Hz system), are offered by the remote system. For protection reasons, this board performs below 0.5-1% error at nominal value and 35p u range, and for metering accuracy, it surpasses Class 0.25. A serial data stream is created from the output of the analog-digital (A/D) converter, some supervisory and data control signals, and light pulses, which are then coupled into the data fiber [15]. Apart from the data stream, the remote board's voltage is also observed for safety purposes and to regulate the laser power.

A very accurate voltage source that can be linked to the data line from the local unit while in a calibration or test mode is built into the layout in order to guarantee the ability for a remote calibration of the electronic circuitry [16]. The schematic diagram of the OPDL system are shown in Fig. 4 and Fig. 5.

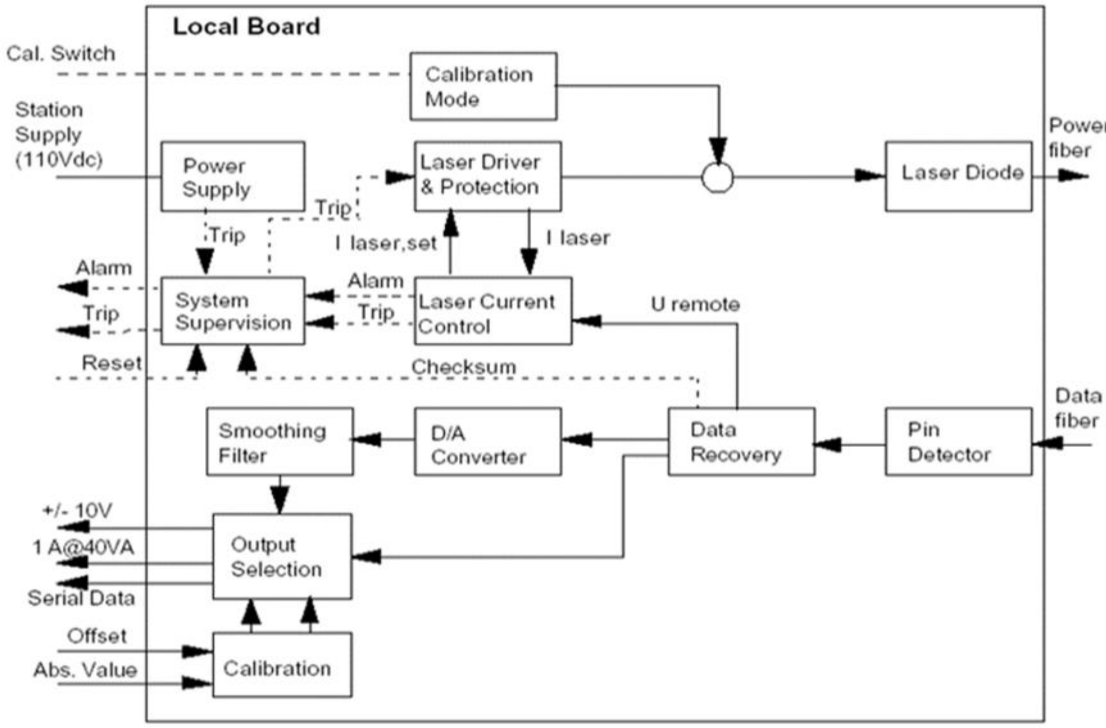

Figure 4: Internal Architecture of the OPDL Local Module

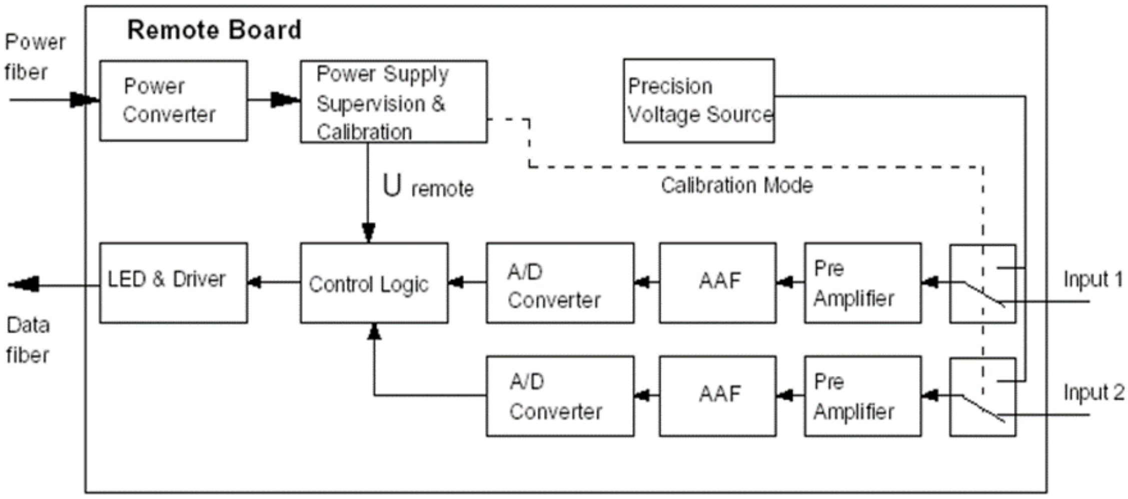

Figure 5: The Remote Architecture of the OPDL Module

III. BENEFITS DERIVED FROM USING OPTICAL TECHNOLOGY

The main benefits of this optical technology over traditional inductive and capacitive measuring transformers are as follows: protection (<1% error; 20–30 p.u. range) and good metering performance (better than Class 0.2) [17]. The comparison of the OCT and the conventional CT is shown in Table 1.

Table 1: Comparison of traditional CT to OCT

Disadvantages of Traditional CT	Advantages of Optical Current Transformer
Potential for disastrous outcomes	Cannot blow up. Safe and environmentally benign (doesn't need SF6 or oil)
Saturation under fault current	No saturation under fault current
Effects of ferro-resonance	No ferro-resonance effects since there is no iron
Hysteresis effects	No hysteresis effects
High voltage, with output leads opened	There is no open-circuit risk (fiber cable)
Heavy requiring supports	Lightweight optical sensors

Large Land requirement	Land requirement minimized and easy to relocate
Limited precision (typically 0.3%)	Usually limited by electronics, accuracy meets IEEE Class 0.3 and IEC Class 0.2 standards.
Dependent on EMI effects	Resistance to EMI
Circuit-breakers (CB)	No need for CBs
High cost involved	Reasonably cheap with low maintenance cost
Short Range	Wide Dynamic Range

IV. APPLICATIONS OF OPTIC FIBER SENSOR

1 Partial Discharge in Power Transformers: Detection Using Optical Fiber Sensors

Power transformers can experience a major breakdown at any time, which can lead to severe oil spills, fires, extensive destruction of nearby equipment, as well as a significant interruption in service. Partial discharges (PDs) are frequently a factor in dielectric breakdowns caused by the deterioration of the insulation property of transformer oil, as is frequently observed in the Nigerian electricity sector. Partial discharge activity should be studied and monitored in order to identify early warning signs of insulation issues, prevent serious failures, and limit costly repairs [18]. In this regard, optical fiber sensor-based detection plays a crucial role.

Fiber Optic Sensors With An Operating Temperature About 2000°C

Experts have developed a variety of sapphire fiber sensors and associated technologies through groundbreaking research. In particular, the power industry's requirements for monitoring and management of high temperature industrial processes can be met by the developed sapphire fiber-based sensors, which can be utilized to measure temperature, strain, and pressure in high temperature (of about 2000^0C) settings [19]

2 Fiber Sensor Technologies For Efficient And Economical Oil Recovery

In order to monitor pressure, temperature, oil flow, and acoustic waves in downhole oil wells, researchers are creating dependable, reasonably priced optical fiber sensors. These kinds of data are vital to oil corporations because they allow them to control oil recovery and maximize its efficiency. Due to the sensors' short lifespan, high cost, and limited ability to endure the severe conditions of the downhole environment, the full extraction of oil reserves from existing reservoirs has been impeded [20].

When light propagated through Faraday sensors, linearly polarized light underwent rotation due to the influence of a magnetic field. The amount of rotation observed for a given substance was found to be proportional to both the field strength B and the light's travel distance through the medium [3][6].

This equation can be used to express this rotation as follows:

$$r = dl\ B\ V\ e \qquad (a)$$

where V is a number known as the Verdet constant and is defined as the rotation per unit path per unit field strength. B is the magnetic induction in teals, l is the length of the light path in meters, and e is the angle of the rotation in minutes of arc [4][5].

3 The Idea behind the Faraday Effect

Ampere's law states that equation (a) can be rewritten as follows when linearly polarized light surrounds a current-carrying conductor:

$$\boldsymbol{IV\ n\ r = u\ e} \qquad (b)$$

where n denotes the number of turns in the optical route and u denotes the material's permeability. Because the rotation angle "e" is directly proportional to the contained current, the OCT is virtually entirely based on equation (b) as of late [4][5].

V. CONCLUSION

Innovation in a variety of domains will impact our industry's future as it changes. From a technological and financial standpoint, measuring voltage and current using optical means appears to be highly appealing, particularly for high-voltage systems where it allows for the elimination of costly high-voltage insulations. If Nigeria's national energy road map fully incorporates these technological advancements, we will gain from them in the areas of fiber optics, electronic design, power engineering, and software design. Because optical sensor technology may be applied to both inside and external substations, it has the potential to completely transform Nigeria's transmission and distribution sector. Optical sensors can be used in ways that are not feasible with traditional analog signals when the signal is intrinsically digital. Visualize a fully computerized substation that includes digital communication between switches, breakers, supervisory control and data acquisition (SCADA) functions, meters, relays, sensors for voltage and current, controllers, and meters. Substation design, maintenance, testing, and commissioning can be greatly expedited by making use of the fundamental benefits that these techniques offer, namely linearity and the impossibility of overload or high-voltage damage. Additional benefits include their bandwidth and cost, as was already outlined above.

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