All-optical busbar differential protection scheme for electric power systems

M Nasir[*+]*, A Dysko*[*]*, P. Niewczas*[*]*, G Fusiek*[*]

[*]*Institute for Energy and Environment, Electronic and Electrical Enginering Department.*
University of Strathclyde, Glasgow – UK. [+]*Email: muhammad.nasir@strath.ac.uk*

Keywords: Faraday rotator, optical devices model, differential protection, Jones matrix formalisation, optical measurement.

Abstract

This paper proposes a novel implementation of a differential protection scheme using magneto-optic current sensors. The proposed all-Optical Differential Protection (ODP) scheme utilizes inherent properties of magneto-optic sensors connected in series to perform differential protection functionality. In order to demonstrate the validity of the proposed scheme, all constituent components such as optical fibre, polarisers and Faraday rotators have been modelled using the Jones matrix representation. Through selected simulation-based case studies, including external and internal (high resistive and solid) faults, the paper demonstrates that the proposed novel ODP scheme for busbar protection meets the protection relaying performance criteria in terms of discrimination, sensitivity, stability, as well as ultra-high speed of operation.

1 Introduction

In the conventional busbar differential protection schemes, iron core current transformers (CTs) or equivalent electronic current transformers (ECTs) are applied to measure current in protected circuits. CTs suffer from measurement accuracy issues resulting from the existence of the magnetizing current. This can be worsened by saturation causing significant current measurement errors, potentially leading to erroneous relay operation and false tripping of the circuit breaker (CB). The effect is particularly significant in busbar protection applications as many CTs are often connected in parallel and thus increasing the influence of the magnetising current. Development of an optical current transducer (OCT) for protection purposes is aimed to resolve the CT saturation problem and other technological shortcomings [1-4]. Significant progresses have been made in recent years to realize such OCTs. A number of methods have been implemented which can be grouped under two broad types, namely “hybrid” optical sensing [5], exploiting a combination of primary current transducers, magnetostrictive or piezo-electric sensors and optical strain sensors that are interrogated remotely, and “pure” optical sensing [6], utilising a range of intrinsic or extrinsic optical sensors based on the magneto-optic Faraday effect. Moreover, a range of research activities in the area of optical current sensing for monitoring, metering and protection purposes are still underway [7-10].

ODP schemes have been reported extensively in open literature. These schemes apply the general method of modern numerical protection where currents are measured by OCT, digitized, and analysed using numerical algorithms based on the selected protection scheme [11-13]. Therefore, such schemes could be termed as “mixed optical-numerical protection”. They generally consist of two steps: a conversion process and a process of substitution into protection scheme algorithm. The first step (the conversion process) is the conversion of the measured current from analogue to optical modulation that is performed by an OCT. The second step is to translate the optical signals into digital values which are then used by an algorithm within a numerical relay to perform a given protection relaying scheme.

In contrast to the previous method, this paper introduces a new method to perform an ODP scheme that could be termed as “**all-optical protection**”. An ODP scheme for busbar protection based on the circulating current differential protection principle is proposed. The proposed ODP scheme is implemented using a carefully designed arrangement of basic optical devices without the need for complex numerical processing at the second step conversion in the previous method. The proposed scheme utilizes all optical elements to perform the operational characteristic of differential protection using configuration of optical devices such as a Faraday rotator, linear polarizer, polarized light source and optical detector. In this design, inherent operational functionality is realised using a series connection of optical devices that follow the current differential connection pattern. Such a design is intended to minimize the complexity of the ODP configuration while retaining the quality of the differential protection scheme. Due to the purely optical nature of the scheme, the need for digitisation of the sensor outputs and digital signal processing within the relay are eliminated; therefore, the proposed scheme has the potential for the reduction of the total operating time.

This paper begins with theoretical overview of the circulating current protection scheme and modelling of optical components in Section 2. A methodology to design a novel all-optical differential protection scheme configuration is explained in detail in Section 3. Moreover, the results of computer simulations are given in Section 4. Finally, Sections 5 and 6 cover the discussion and conclusions, respectively.

2 Theoretical background

2.1 Circulating current differential protection

The basic principle of a circulating current differential protection scheme is presented in Fig. 1.

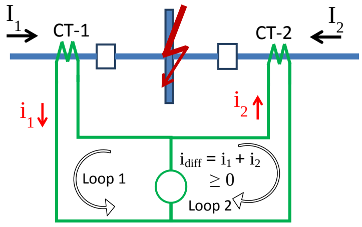


Fig. 1. Principle of circulating current differential protection.

The scheme is based on Kirchhoff's current law which maintains that the directed sum of all currents in the healthy element is equal to zero (under ideal measurement conditions), Therefore, a current sum which is not equal to zero would indicate an existence of a fault in the protected element.

Relay threshold setting is typically introduced in the differential protection to cover any non-ideal conditions. The differential relay generates no tripping signal when the differential current i_{diff} is smaller than the threshold setting, and the tripping signal is produced only when differential current is greater than the setting [14-16]. The differential relay operation logic can be stated as follows:

$$\begin{array}{ll} & \{\; i_{diff} = |I_1 + I_2| \;; \\ \textit{No trip is generated, if:} & \quad i_{diff} \leq i_{setting} \;; \\ \textit{Trip is generated, if:} & \quad i_{diff} > i_{setting} \;\} \end{array} \qquad (1)$$

where i_{diff} is the differential current in the relay branch, i_1 and i_2 are phasors derived from secondary currents of CT-1 and CT-2 flowing in loop 1 and loop 2 respectively.

2.2 Optical component modelling using Jones principles

For the purposes of modelling the optical devices and the ODP scheme configuration, polarized light and all optical parts (sensors, optical fibre, polarizers, wave-plates, etc.) can be expressed in a matrix which use a **[2x2] matrix** representation. Since in this method polarized light will be used as a carrier transverse wave to interrogate Faraday rotators, the polarized light has to use a representation which can describe its characteristics in terms of two linear orthogonal polarizations. As a consequence, the polarized light could be expressed by the two element vector, **E**, to describe its state of polarization (SOP). All optical parts such as the faraday rotator, linear polarizer, and optical fibre should comply with the modelling process based on the Jones matrices [17-21].

In order to incorporate all models of optical devices in an integrated framework, Jones formalization had been introduced as a formal system for analysing light and optical material interaction. The electric field component of the transverse wave, $\mathbf{E}_o$, exiting a single device that introduces an optical effect **J** when incident light, $\mathbf{E}_i$, passes through this media, is given as

$$\mathbf{E}_o = \mathbf{J} \cdot \mathbf{E}_i \qquad (2)$$

The effect of multiple optical devices can be determined by simple multiplication of the matrices where output of the first device becomes input for the next device. This principle can be described by

$$\mathbf{E}_o = \mathbf{J}_m \cdot \mathbf{J}_{m-1} \cdot \mathbf{J}_{m-2} \cdot \mathbf{J}_{m-3} \ldots \mathbf{J}_3 \cdot \mathbf{J}_2 \cdot \mathbf{J}_1 \cdot \mathbf{E}_i \qquad (3)$$

where m is a number of optical components in the path.

The Jones formalization is an efficient method in numerical modelling of polarized light, optical devices, and interaction between light and optical materials [17].

2.3 Faraday magneto-optic principle

When linearly polarized light passes through a magneto-optic medium, such as optical glass or TGG crystal, the direction of polarization is rotated in proportion to the magnetic field component parallel to the light propagation direction (refer to Fig. 2.a). The angle of rotation of the polarized light (θ) is proportional to the magnetic field intensity vector (H) and the cosine of the angle between the field and the direction of the light wave propagation. In the transparent material the effect is described by Becquerel's formula (4) which is well known as the Faraday effect [22, 23]:

$$\theta = V \cdot \int_L \mu \cdot H \cdot dl \qquad (4)$$

where, V is the material Verdet constant related to material characteristics, wavelength, and temperature; dl is the differential vector along the direction of light propagation; and L is the distance of the polarized light traversing the Faraday magneto-optic material.

Since μH can be substituted by B (magnetic field strength), (μ is the permeability of the magneto-optic material), equation (4) can be expressed as

$$\theta = V \cdot \int_L B \cdot dl \;\; = V \cdot B \cdot L \qquad (5)$$

3 Design of all-optical protection scheme

3.1 Sensor design

The proposed transducer exploits a Faraday rotator (FR) element centred in a solenoid used to induce magnetic field in the rotator as a result of current flowing through the coil. This is illustrated in Fig. 2.

The state of polarisation (SOP) of light exiting the Faraday rotator can be expressed by the angle of rotation θ:

$$\theta = V \cdot L \cdot k \cdot n' \cdot i \tag{6}$$

where k is a factor for magnetic field., n' is the number of turns per unit length, i is the measured current. Thus, the angle of rotation is proportional to the measured current on primary side.

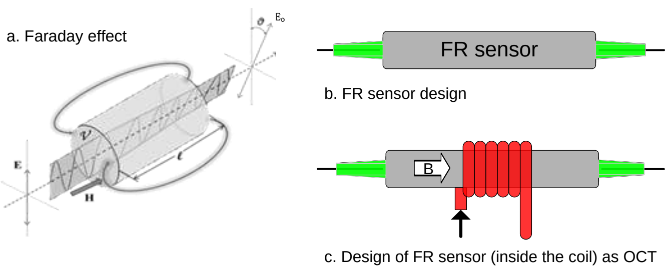


Fig. 2. Optical current transducer employing Faraday magneto-optic effect

3.2 Design and principle of ODP scheme

The ODP scheme can be realized by combining the circulating current differential principle with both Faraday rotator sensors (illustrated in Fig 2) connected in series using a section of optical fibre. The combined optical rotation is a sum total of the outputs produced by the two sensors. This is described by the following equation:

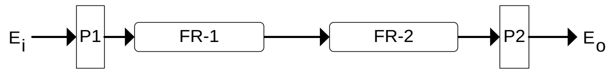
$$\theta_{diff} = \theta_1 - \theta_2 \tag{7}$$

where θ_1 and θ_2 are the light state outputs from Faraday rotator sensor 1 dan 2 respectively.

To successfully implement the scheme, three conditions must be fulfilled. Firstly, polarized light is required for operation of the scheme. Secondly, the differential current detection should be realised by the optical circuit as much as possible, with minimal involvement of electronic signal processing. Thirdly, the scheme must provide adequate performance in terms of sensitivity of the differential current detection.

The three requirements of the ODP design can be fulfilled by the appropriate arrangement of basic optical devices as shown in Fig. 3. It is noted that two linear polarizers in Fig. 3 must be placed with the transmission axis (TA) at 90° or ‘crossed position’ with respect to each other. The Faraday rotator sensors are connected in series and placed between the two polarisers (P1 and P2). Their electrical terminals must be connected in such a way that the polarisation rotations of the individual sensors cancel out when there is no fault condition (no differential current present). Such is an ODP scheme follows the differential relaying connection requirement.

The scheme can be extended to more than two Faraday rotator sensors, for example applied to a multi-terminal circuit. Critically, the optical fibre is required to maintain the SOP of polarized light which has to travel along the protection scheme configuration (Fig. 3). This condition is fulfilled when relatively short sections of fibre (metres) are employed.



E_i / E_o : light input / output → : FO link,

P1 / P2: polarizer-1/2 FR-1/2: optical sensor-1/2

Fig. 3. Optical differential protection scheme configuration for 2 branches

In order to analyse the polarized light interaction within optical components, by following equation (3) and Fig. 3, the input and output relationship of polarized light in the complete ODP scheme can be expressed using the Jones matrices formalism:

$$\mathbf{E}_o = \mathbf{FO5}_9 \cdot \mathbf{P2}_8 \cdot \mathbf{FO4}_7 \cdot \mathbf{FR2}_6 \cdot \mathbf{FO3}_5 \cdot \mathbf{FR1}_4 \cdot \mathbf{FO2}_3 \cdot \mathbf{P1}_2 \cdot \mathbf{FO1}_1 \cdot \mathbf{E}_i \tag{8}$$

where **FO1**, **FO2**, **FO3**, **FO4** and **FO5** are matrices representation of fibre optic sections 1, 2, 3, 4 and 5 respectively, **P1** and **P2** are matrices representation of polarisers 1 and 2, **FRl** and **FR2** are matrices representation of Faraday rotators 1 and 2, and $\mathbf{E}_i$ is matrices representation of the polarized light input.

Since each optical Jones matrix in equation (8) is in the similar Cartesian coordinate system that are linked together by $\mathbf{E}_o$ and $\mathbf{E}_i$; therefore, Cartesian Jones matrix transformation must be applied to the optical device if it has been rotated or is under coordinate rotation. As the representation of circulating current differential protection in the electrical domain is stated by equation (1), the similar expression in optical domain is stated by equation (8). For busbar with more than 2 branches / circuits, equation (8) could be extended by adding a number of FR and FO links based on Kirchhoff Current Law.

In addition, the polarization states or the light intensity at the exit of P2 or FO is then monitored by a detector unit. The output signal can be described as [24, 25]

$$I = | S | = (\mathbf{E}_o \cdot \mathbf{E}_o^*) / Z \tag{9}$$

where $\mathbf{E}_o$ is electric field component of the transverse wave, $\mathbf{E}_o^*$ is transpose of the complex conjugate $\mathbf{E}_o$ and Z is total impedance of the medium which is the ratio of the electric field to the magnetic field.

The detector unit consists of photo-detector and optoelectronic threshold detector. A comparison process is carried out by a simple optoelectronic threshold detector to detect a fault occurrence through all-optical comparison that compares between power modulation outputs and the threshold level. The output then informs a decision either to trip or no-trip as part of optical protection relaying operation.

In practical term, the first condition, no-trip signal is generated by the ODP when the optical power modulation is less than the threshold setting. This condition takes place when rated current flows at the primary side (no-fault condition) or a fault occurs at outside of protected circuit (external fault) which cause both Faraday rotator outputs to have the same states but in opposite direction – therefore the sum of light rotations is zero. Conversely, a trip signal is generated by the ODP when the optical power modulation is greater than the threshold setting. This condition occurs when an internal fault occurs at protected circuit which cause both Faraday rotator outputs to have different states - therefore the sum of light states is greater than zero.

4 Case studies

To assess performance of the proposed ODP for busbar protection, a Matlab®/ Simulink model of the scheme was built. The model consists of a test power system (Fig. 4), the light source wavelength of 1550 nm, differential protection model based on equation (8) and the output detector using equation (9).

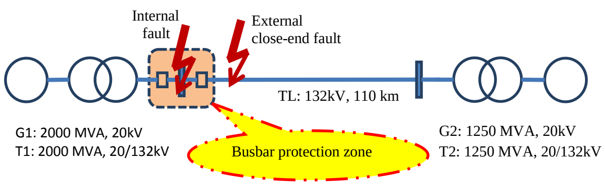


Fig. 4. Power system model for optical differential protection scheme

In general, two main fault conditions are considered, i.e. internal and external fault with respect to the protected zone. Internal fault also includes high resistive fault with R_f=200 Ω. The fault scenarios are summarised in Table 1. The fault inception time is assumed to be 0.020 second and the power of optical source is 10 mW. FO attenuation is 0.020 dB/km and other losses such as Fresnel reflection is calculated using the Matlab program. Threshold setting is chosen to 23.328 μW as an average value of measured optical power modulations between solid external fault and high resistive internal fault. This ensures that there is a comfortable margin for both sensitivity and stability of the scheme. Additionally, a small stabilising delay of 0.5 ms has been applied to prevent spurious tripping on random noise.

Case	Fault location	Fault type	Fault resistance	Remarks
1.a	internal	L-G	R_f=200 Ω	Fig. 5
1.b	internal	L-G	R_f=0 Ω (solid)	Fig. 6
2	external	L-G	R_f=0 Ω (solid)	Fig. 7

Table 1: Location, type and resistance of simulated faults

For verifying protection sensitivity, Case-1.a with high resistive fault condition was used. The simulation results indicated that the ODP could detect an occurrence of a fault which provides power modulation with peak value of 23.505 μW. By passing this optical power modulation into simple threshold comparison, the protection generates a trip signal as illustrated in Fig. 5.

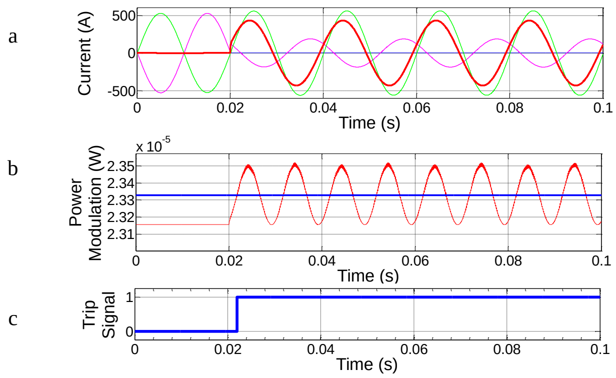


Fig. 5. ODP Scheme simulation for internal high resistive fault: a. Measured fault current, b. Optical power modulation, and c. Trip signal.

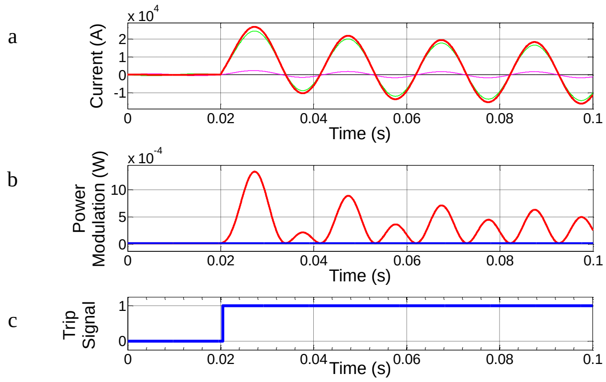


Fig. 6. ODP Scheme simulation for internal solid fault: a. Measured fault current, b. Optical power modulation, and c. Trip signal.

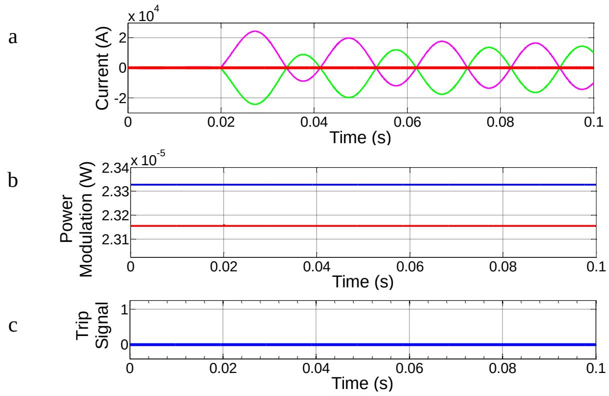


Fig. 7. ODP Scheme simulation for external solid fault: a. Measured fault current, b. Optical power modulation, and c. Trip signal.

In case of a solid internal fault (refer to Fig. 6) the power modulation is much higher than the assumed threshold [1.332 mW (-8.75 dB) compared to 23.328 μW (-26.32 dB)] which demonstrates very good level of dependability.

The ODP stability/security attribute is tested by simulation Case 2 with external solid fault (refer to Fig. 7). In this case the power modulation level is 23.156 μW (-26.35 dB) which is below the assumed threshold.

Another protection attribute is the speed of operation. The ODP total operating time consists of three consecutive time intervals which are: the differential output, optical power comparison, and decision processing time (including any stabilising time delays and tripping logic). The differential output processing time is very short because it uses polarized light to conduct instantaneous differential processing. In the presented case it is approximately 3.28 μs with FO length around 500 m and the light speed in the medium *c*/*n* (where *c* is the light constant and *n* is refractive index of optical medium). The remaining processes which are the photo-detection and comparison of the optical power modulation and decision processes are similar to typical numerical relay processing time, which in this case could be achieved in less than 2 ms (refer to Fig. 8 and Table 2).

It is also worth mentioning that the application of Faraday rotators which substitute iron core CTs helps in eliminating potential saturation problems.

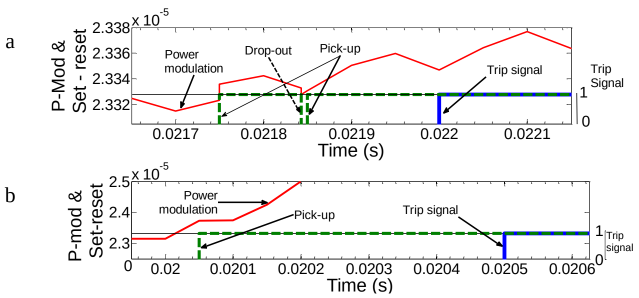


Fig. 8. Time traces simulation of ODP scheme for different fault resitypes: a. Internal high resistive fault, and b. Internal solid fault.

Case	Incipient Fault at (s)	Differential status (ms)			Trip at (s)	ODP response time (ms)
		No. Attempt	Pick-up	Drop-out		
1.a	0.02000	1	1.75	1.825	0.0220	2.0
		2	1.85	—		
1.b	0.02000	1	0.05	—	0.0205	0.5
2	0.02000	—	—	—	—	—

Table 2: Pick-up, drop-out and tripping time of ODP scheme

5 Discussion and Conclusions

In this paper, a basic model of the all-optical differential protection scheme for busbar protection based on a combination of Faraday rotators and other passive optical devices modelled using Jones principles has been developed. The proposed ODP model has the ability to generate optical modulation output as the SOP sum of all FR outputs that corresponds with the differential of measured current. Therefore, the ODP scheme is an alternative of an electromagnetic relay type of circulating current differential protection scheme. The proposed ODR scheme consists of a simple optical arrangement and need no complex procedure to conduct its function as a differential protection. Thus, the proposed technique of all-optical busbar differential protection scheme does not merely use the optical sensing techniques to derive the numerical replica of the current but also utilises optical devices to directly implement the fundamental principles of differential protection. The scheme is a simple series connection of optical components without the need for complex signal processing. The required processes are conducted by direct subtraction of polarisation rotations as a distinctive primary process of the ODP scheme to shorten the reaction time. Through systematic simulation-based case studies, the proposed novel configuration has met the protection relaying key performance criteria such as selectivity, sensitivity, security, dependability and speed of operation. The simulation have demonstrated that an immediate response to an increase in differential current can be achieved using optical system and the all-optical protection scheme providing a fast-acting and highly discriminative fault detection system for bus bar protection.

The method that was presented in this paper could provide a contribution to basic development of optical differential protection framework. Even though the ODP scheme has been demonstrated on a busbar protection, the proposed method has a potential to be applied as a differential protection for short transmission lines (up to 10km). Further investigation is needed to rigorously assess such applications.

Although a fault detection system can be realised for a basic protected circuit, such as a bus bar, due to the small value of optical power modulation during high resistance faults, the intensity of optical power modulation may not be sufficient to detect such a fault. These issues will be addressed by the future research. Simulation results that are presented in this paper were achieved with assumption that the optical sensors had similar characteristics. It should be noted that optical power attenuation is neglected due to bending of optical fibre. Future work will concentrate on addressing these issues and will assess the influence of these effects on the proposed system performance. This will be achieved both through improved modelling and laboratory testing of the system prototype.

Acknowledgment

The author would like to thank Directorate General Higher Education of Republic of Indonesia (aka Dikti) for their support through BPPLN scholarship programme.

References

[1] IEEE, "Optical current transducers for power systems: a review," *Power Delivery, IEEE Transactions on*, vol. 9, pp. 1778-1788, 1994.

[2] J. D. P. Hrabluik, "Optical current sensors eliminate CT saturation," in *Power Engineering Society Winter Meeting, 2002. IEEE*, 2002, pp. 1478-1481 vol.2.

[3] K. Bohnet, *et al.*, "Fiber-Optic Current and Voltage Sensor for High-Voltage Substations," *16th International conference on Optical Fiber Sensors,* p. 3, 13-17 october 2003 2003.
[4] S. Kucuksari and G. G. Karady, "Experimental Comparison of Conventional and Optical Current Transformers," *Power Delivery, IEEE Transactions on,* vol. 25, pp. 2455-2463, 2010.
[5] L. Dziuda, *et al.*, "Laboratory evaluation of the hybrid fiber-optic current sensor," *Sensors and Actuators A: Physical,* vol. 136, pp. 184-190, 2007.
[6] M. H. Samimi, *et al.*, "Open Core Optical Current Transducer: Modeling and Experiment," *Power Delivery, IEEE Transactions on,* vol. PP, pp. 1-1, 2015.
[7] C. T. Law, *et al.*, "Fiber-Optics-Based Fault Detection in Power Systems," *Power Delivery, IEEE Transactions on,* vol. 23, pp. 1271-1279, 2008.
[8] A. P. Steer, *et al.*, "Optical fibre current sensor for circuit protection," in *Developments in Power Protection, 1989., Fourth International Conference on*, 1989, pp. 296-300.
[9] R. B. Amin Moghadas, Mehdi Shadaram, "An Innovative Fibre Bragg Grating Sensor Capable of Fault Detection in Radial power Systems," presented at the 4th Annual IEEE System Conference 2010, 2010.
[10] P. Orr, *et al.*, "Flexible protection architectures using distributed optical sensors," in *Developments in Power Systems Protection, 2012. DPSP 2012. 11th International Conference on*, 2012, pp. 1-6.
[11] H. Y. Li and P. A. Crossly, "Design and evaluation of a current differential protection scheme incorporating a fiber optical current sensor," in *Power Engineering Society Summer Meeting, 2000. IEEE*, 2000, pp. 1396-1400 vol. 3.
[12] M. Nasir, *et al.*, "Development of Power System Differential Protection Based on Optical Current Measurement," in *48th International Universities' Power Engineering Conference*, Dublin, 2013.
[13] G. Fusiek, *et al.*, "All-optical differential current detection technique for unit protection applications," in *International Instrumentation and Measurement Technology Conference 2013*, Minneapolis, USA, 2013.
[14] J. Holbach, "Comparison between high impedance and low impedance bus differential protection," in *Power Systems Conference, 2009. PSC '09.*, 2009, pp. 1-16.
[15] P. M. Anderson. (1999). *Power System Protection*.
[16] GEC. *Protective Relaying Application Guide*.
[17] R. C. Jones, "New Calculus for the treatment of Optical Systems: I-VII," *Journal of the Optical Society of America,* vol. 31,32,37,38, 1941-1948.
[18] A. J. Rogers, *Polarization in optical fibers*: Norwood, MA : Artech House, 2008.
[19] R. M. A. Azzam, Bashara, N. M, *Ellipsometry and Polarized Light*. Amsterdam: Elsevier Science BV, 1987.
[20] S. Kucuksari and G. G. Karady, "Complete Model Development for an Optical Current Transformer," *Power Delivery, IEEE Transactions on,* vol. 27, pp. 1755-1762, 2012.
[21] *Handbook of optical systems*: Weinheim ; Great Britain : Wiley-VCH, 2005.
[22] E. Hecht, *Physics*: Brooks/Cole Pub., 1994.
[23] R. D. Guenther, *Modern optics*: New York : Wiley, 1990.
[24] F. L. Pedrotti, *et al.*, *Introduction to Optics*: Pearson Prentice Hall, 2007.
[25] C. A. Dimarzio, *Optics for engineers*: Boca Raton, FL : CRC Press, 2012.