Design of Polarimetric-Based Optical Current Sensor for Electric Power System Application

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Abstract. Many problems arise in the electric power protection system due to applying a ferrous core current transformer (CT). One of the most crucial problems is a magnetic saturation issue, which tends to cause a measurement error on the secondary side of the CT and could reduce the performance of the protection system. An alternative solution to this issue is the needs to develop an electric current sensor utilizing optical materials. A polarimetric-based optical current sensor (OCS) is a technique considered to be compatible with the future smart grid environment. The OCS principles are based on the magneto-optic Faraday effect that could produce optical rotation in the optical media when a polarized light propagates in those materials. Due to the linear and circular birefringence effect in optical fiber medium are exist, therefore, in this paper the OCS and its associated elements are modelled by considering the birefringence effect in the optical sensor system including optical fiber links. Then, the OCS model is translated to a computer simulation program using a computer application software. Orientation of the second polarizer (analyzer) to the first polarizer in the simulation were conducted using two different angles which are angle $\alpha$ of 45° and 90°. Performance assessment of the OCS model is presented using two various electric current of the power system test to investigate the presence or absence of the saturation effect that may arise in the polarimetric-based optical current sensor model. The simulation results have provided that the saturation effect disappear in the simulation and the analyzer orientation angle $\alpha$ of 45° gives better performances of optical power modulation than the other angle.

1. Introduction

The conventional voltage and current transformers are intended to provide a scaled down replica of primary voltage and current, respectively, from transmission levels down to a suitable level for protective relays. As a consequence of reducing the electrical quantities in magnitude the protection relays can be designed as relatively small and inexpensive devices. Both instrument transformers also provide insulation of the low voltage relay equipment from the high voltage power system.

Magnetic saturation phenomenon in CTs due to the use of ferrous materials as CT’s core is one of the main limitations of the conventional CTs. The saturation process is initiated by the creation of high flux density in the iron core that can be caused by several factors such as high fault currents with or without a dc offset, residual flux, high secondary burden, or a combination of these factors. The saturation occurs when the flux density exceeds the design limits of the CT core. As a result, accuracy of the CT becomes poor because the secondary current is lower in magnitude than the value expected from the nominal ratio of the CT. Another undesirable effect is the introduction of harmonic components.
into the output current that may cause a distortion [1,2]. This, in turn, can potentially affect the protection relay performance.

Other potential problems of the conventional instrument transformers may result from size, weight, and insulation requirements. Increasing the power system generating and transfer capacity requires a bigger CT size CT while increasing system voltage requires a better insulation and suitable dimensional design. It will result the massive CT’s structures that ultimately consume high cost.

An alternative solution for avoiding saturation problems is the utilization of a different CT construction without ferrouscore. Some CT manufacturers have developed alternative designs such as air-gap CT, linear coupler, Rogowski coil, hybrid optical and pure optical current transducer techniques [3]. The optical current sensing techniques attract researcher to develop a new design of optical current transducer for electric power system applications.

Optical systems for high voltage current measurements that is known as optical current transducer have been developed in early 1970s when several different approaches were well documented [4-6],[7]. The optical current transducers have several advantages over the conventional CT due to their small size, light weight, low cost, absence of ferromagnetic resonance problems, large linear measurement range, broad response frequency bandwidth and electromagnetic interference immunity [8,9],[10]. Therefore, this paper introduced a design of polarimetric based optical current sensing technique.

2. Materials and methods

A formal system for analyzing both the light and optical material interaction is known as Jones Formalization. shown in figure 1. It provides an efficient method for describing the polarized light and propagation of the electric field through several polarizing components at the amplitude level [11]. When the polarized wave incident $E_i$ propagates in a single polarizing optical system $J$, one or more modified TE exiting waves $E_o$ are emerged from the optical system. This Jones formalization is constrained in equation (1)

$$E_o = J E_i$$

A fundamental difference between optical current measurements and conventional CTs is in the signal power involved. The secondary signal of a conventional CT has a power level of several watts, whereas the power in an optical current measurement is only a few micro watts ($\mu$W). In general, the current being measured in an optical current measurement is represented as modulated light.

The most common optical technique for current sensing is polarimetric method which is based on the Faraday rotation effect that is exhibited by magneto-optic crystals. This method has been reported in literatures [3,12-16].

Crystal materials for the optical current sensor application could be diamagnetic, paramagnetic or ferromagnetic crystals [8] such as optical glass MOC-series, SF-6 glass, or Terbium Gallium Garnet (TGG) crystal. These magneto optic crystals become an actively optical medium when it is under
magnetic field effect. If a linearly polarized light incident $\mathbf{E}_i$ passes through the actively optical medium, simultaneously the direction of the polarized light state emerging $\mathbf{E}_o$ is rotated parallel to the light propagation direction in proportion to the magnetic field $\mathbf{H}$ as displayed in figure 2 [17].

In term of a quantitative relationship, the rotation angle of the polarized light $\theta$ is proportional to the magnetic field $\mathbf{H}$ and the cosine of angle between the direction of the magnetic field and the direction of the light propagation. This statement is described by Becquerel's formula which is well known as the Faraday effect [18,19]:

$$\theta = V \mu \int_0^L \mathbf{H} \, dl$$

where, $V$ is the material Verdet constant related to material characteristics, wavelength, and temperature; $\mu$ is the permeability of the magneto-optic material; $\mathbf{H}$ is magnetic field; and $dl$ is the path element of Faraday magneto-optic material.

A typical arrangement of optical components in a Faraday sensor is shown in figure 3. A light beam is generated from the light source then passing to a Faraday magneto-optic crystal via a section of fibre optic, a GRIN lens collimator and a first polariser (a polariser). When a magnetic field is applied as the effect of the current flowing, the linearly polarized light is rotated by an angle $\theta$ proportional to the applied field. The light output is passed to a photo detector via a GRIN lens collimator and output fibre. The photo detector is utilized to translate modulated light into optical power modulation.

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3. Results and discussion

The proposed method has been implemented to a case study which is a power system network as shown in figure 4.

![Figure 4. Single line diagram of a power system for case study](image)

The optical sensor model has to be developed using Jones Formalization and applied into Matlab application software. Several optical device models and the power system model have to be combined and defined in the Matlab environment in order to facilitate for computer simulation.

Simulations of the test power system were conducted to determine two kinds of current i.e. normal operation and fault currents, that flow in the line where the optical sensors were equipped. Orientation of the second polarizer (termed as analyzer) is arranged at two different angles which are at angle $\alpha$ of $45^\circ$ and $90^\circ$. These two angles of analyzer orientation have been applied in the simulation. For the simulation purposes, light source has center wavelength of 1550 nm.

The optical power modulation output for these two angles of the analyzer orientation are displayed in figure 4 and figure 5 as response to the normal operation current. These results could be used to compare the analyzer performance in the optical sensor application.

![Figure 5. Optical power modulation with analyzer angle $\alpha$ of $45^\circ$ for normal operation current.](image)

Comparing both figure 4 and figure 5 show that the analyzer arrangement at angle $\alpha$ of $45^\circ$ with respect to the polarizer provides better output in terms of optical modulation shape than angle $\alpha$ of $90^\circ$, where the first analyzer arrangement produce a similar pattern of the optical power modulation with normal operation current pattern.
Figure 6. Optical power modulation with analyzer angle $\alpha$ of 90° for normal operation current.

Another result could be derived from both figures above at the same current magnitude of 1410 A that the first angle of analyzer arrangement provided higher optical power modulation output which is the peak value of 9.60E-04 W, whereas the second arrangement could produce the peak value of 7.7E-08 W.

The same results of optical power modulation shapes were also obtained for the fault current simulations as shown in figure 6 and figure 7.

Figure 7. Optical power modulation with analyzer angle $\alpha$ of 45° for the fault current.
Figure 78. Optical power modulation with analyzer angle $\alpha$ of 90° for the fault current.

The optical power modulation shape has the same form when the analyzer was set to the angle $\alpha$ of 45°. For the same fault current with peak value of 23.3E+04, the optical power modulations for the first and the second arrangement respectively were obtained around 1.14E-03 W and 2.05E-05 W. Therefore, the analyzer arrangement at angle $\alpha$ of 45° with respect to the polarizer could be selected in order to maximize the sensitivity of the optical sensor response.

4. Conclusion
The polarimetric-based optical current sensor have been successfully modelled and simulated. Based on the simulation result evaluation, it can be concluded that the magnetic saturation effect disappears on optical current sensor for this case study. Other result could be provided that the analyzer angle $\alpha$ of 45° with respect to the polarizer position could produce the optical modulation shapes similar to the electric current shapes in both normal and fault condition of power system. Moreover, this analyzer orientation gives also higher optical modulation outputs compare to other angles. This angle generates the sensitivity of the optical sensor response at a maximum value.

The future work will continue to investigate several different optical media that can be utilize in the optical current sensor system. Some assumption in the previous research that neglected the fiber losses and laser beam orientation to optical media will be explored to obtain the general considerations and requirements in the optical current sensor design.

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