Development of Power System Differential Protection Based on Optical Current Measurement

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***Abstract*-A theoretical evaluation of a novel, all-optical differential current protection scheme employing low voltage piezoelectric transducers, fiber Bragg grating sensors and Rogowski coils is presented in this paper. The optical power reflected from the sensors is monitored by means of a single photodetector, whereas fault occurrence is detected by a simple optoelectronic threshold detector. We demonstrate through simulations that an immediate response to an increase in differential current can be achieved even at low voltage levels such as these generated by Rogowski coils providing a low-cost and fast-acting fault detection system.**

***Index Terms*--Current Transformer, Rogowski Coil, Optical Current Measurement, Bragg Wavelength Shift, Reflected Optical Spectrum, Power System Protection, Protection Relaying**

I. Introduction

Conventional instrument transformers for protection convert current and voltage quantities measured on the primary power system side to suitable levels for protection relay input. Although the output quantities are scaled down replica of the input signals, the output must have adequate accuracy for protection applications. In particular, protection systems are required to operate during the periods of transient disturbance (e.g. short circuits) with the output accurately reflecting the shape of the original signal. The errors in transformer output may cause abnormal delays in the protection operation, or cause unnecessary disconnections [1-3].

Although some developments in protection system equipment have improved the CT performance, some difficulties still exist. The main difficulties encountered in the operation of protection systems related to current signal acquisition are CT saturation and high burden. The saturation causes a distortion in the secondary current output. As a result, the relay operation may be delayed or cause unnecessary operation. Increased burden will result in systems which require complex protective relaying schemes with multiple devices fed from the same CTs. These conditions may also contribute to relay mal-operation [1-4]. However, with modern numerical relay technology excessive burden is usually not an issue.

Many recent developments are taking place in the electricity supply industry causing the network and its operation to become increasingly more complex. High penetration of distributed generation has an impact on the network topology and protection system operation. Due to significant variation in magnitude and direction of short circuit currents fixed protection settings may no longer be sufficient. One of the proposed solutions found in technical literature is the application of adaptive protection. This, however, brings the questions of dependability and security of such non-firm arrangements. Such protection will not be affected by network topology changes.

In order to improve the effectiveness of the FBG sensor, a Rogowski coil is proposed to substitute the iron-core CT present in early designs of the FBG current sensor. Rogowski coils produce a linear response, do not have a saturation problem, but provide small power output [5, 6]. The small output problem can be addressed by proper design of the optical sensing element.

Therefore, this paper explores a possibility of implementing differential protection principle using distributed Fibre Bragg Grating (FBG) optical sensing.

II. Measurement System

A. Optical current and voltage sensors

In order to monitor current at two ends of the protected zone, we previously used hybrid fiber-optic voltage and current sensors based on a conventional CT and higher voltage piezoelectric transducers [7-11]. In this application, to eliminate problems related to CT saturation at higher currents, the use of an air-core Rogowski coil is proposed. Since the output voltage of a Rogowski coil is relatively small, a low voltage piezoelectric multilayer stack is employed for the voltage monitoring.

A modified design of an optical hybrid current sensor is shown in Fig 1.

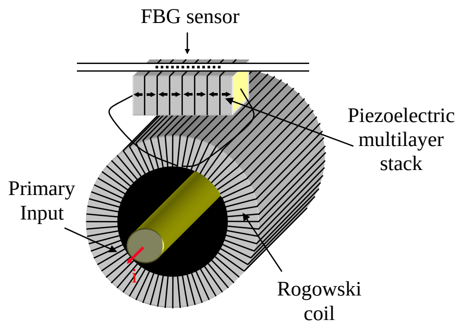

Fig. 1. Optical current sensor employing a Rogowski coil and an optical voltage sensor.

The coil output voltage is related to the primary current by

$$v(t) = -M\frac{di(t)}{dt}, \qquad (1)$$

where M is the mutual inductance of the Rogowski coil, and $i(t)$ is the primary current [6].

The output voltage of the coil generated in response to the primary current is converted to an FBG peak wavelength shifts by means of a low voltage piezoelectric stack strained by the voltage.

The strain induced in the piezoelectric transducer by an external electric field at no mechanical stress can be expressed by

$$\varepsilon = d \cdot E = d \cdot \frac{V}{l} \qquad (2)$$

where d is the longitudinal piezoelectric charge constant, E is the electric field, V is the voltage applied across the piezoelectric material, and l is the length of the material [7].

A relative change in the FBG peak wavelength, $\Delta\lambda_B/\lambda_B$, due to a change in strain, ε, at constant temperature can be expressed by

$$\frac{\Delta\lambda_B}{\lambda_B} = C_\varepsilon \cdot \varepsilon \qquad (3)$$

where C_ε is the strain sensitivity.

For a piezoelectric material considered in this paper (PICMA® HT, Physik Instrumente), the strain sensitivity to voltage is assumed to be 8.8 με/V. This corresponds to an FBG wavelength shift of around 10 pm/V at 1550 nm. The current to voltage ratio of the Rogowski coil (Rocoil) considered in this paper is assumed to be 1000:1 A/V. Consequently, these values were adopted in the simulations discussed in more detail in Section III.

B. Sensor Topology and Fault Discrimination

In power systems which employ differential relay protection all nodes at the ends of the protected zone must measure the electrical current as shown in Fig. 2.

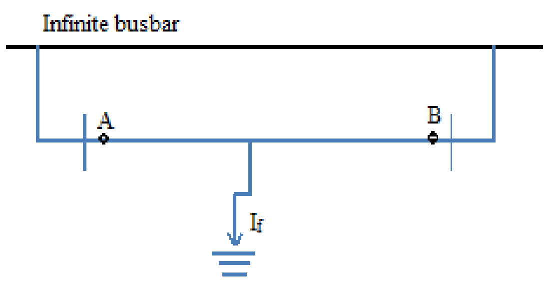

Fig. 2. Differential protection on a two ended circuit.

In general, there are three main fault conditions, i.e. un-faulted condition, fault inside the protected zone, and fault outside the protected zone. When faults or disturbances occur in power system, either inside or outside the protected zone, currents entering or exiting the zone are different in magnitude and/ or phase (direction) [11].

We previously showed that two overlapping gratings having similar spectral profiles reflect a certain amount of spectrum when illuminated by a light source, and the reflected optical power can be detected by a photodetector [11]. When the FBGs are spaced spectrally apart, the reflected power distribution between the sensors is changed, as shown in Fig 3. The amount of reflected power will depend on the separation of FBG spectra and the degree in which they overlap because the total power incident on the photodetector is proportional to the area under the curves shown in Fig. 3.

By placing one FBG sensor at close-end breaker and the other FBG at far-end breaker, a fast-acting fault detection system can be realised for a simple two ended zone, such as transmission line [11]. However, due to the low voltage generated by the Rogowski coil during fault, the depth of optical power modulation might not be sufficient to allow for fault detection. Therefore, the theoretical evaluation of the proposed fault detection system is presented in the following sections.

III. SOFTWARE SIMULATION

To assess the capability of the proposed optical protection system to detect faults, a simulation program was written in LabVIEW (National Instruments). The program allowed for simulations of the Rogowski coil output voltage in response to various primary current levels and optical power modulation in response to various fault scenarios.

It was assumed that both FBG sensors located at two extreme locations of the protected zone experienced the same constant temperature. The optical power generated by the optical broadband source was assumed to be constant in time and over a spectral range of 50 nm. The optical power loss and fluctuations due to the length and bending of the addressing fibre were neglected.

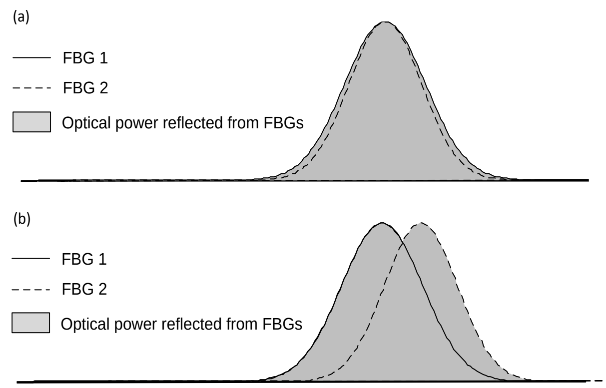

Fig. 3. Optical power distribution between two FBGs: (a) FBGs are aligned; (b) FBGs are spaced apart.

The spectral profiles of FBG sensors were approximated by normalized Gaussian functions:

$$FBG_i(\lambda) = exp\left[\frac{-(\lambda-\lambda_{FBG_i})^2}{2\sigma_{FBG_i}^2}\right] \quad (4)$$

where λ_{FBG_i} is the FBG peak wavelength, i denotes the FBG number, and σ_{FBG} is a parameter determining the FBG bandwidth.

The optical power detected by a photodetector was calculated by integration of the combined FBG profiles over the entire spectrum [11]:

$$P_{det}(\lambda) = \int FBG\,(\lambda)d\lambda \quad (5)$$

where $FBG(\lambda)$ is the total reflection spectrum.

As we previously showed, the narrower FBG bandwidths, the larger depth of power modulation can be observed [11]. The normalized total optical power reflected from two FBG sensors having 0.2 nm bandwidths as a function of the spectral spacing between them is shown in Fig. 4. For a certain wavelength range, the power-spacing relation is linear. By introducing a constant spectral separation between the FBG peaks (0.12 nm in this case), the sensors working range can be shifted into the linearity region allowing to increase the depth of optical power modulation. The width of the linearity region is dependent on the FBGs' bandwidths and can be adjusted according to the requirements.

It should be noted that the depth of power modulation depends also on the sensor sensitivity to voltage/current. By careful sensor design, the FBG shift can be tailored so that the required depth of optical power modulation can be achieved at the maximum current/voltage levels and for the required temperature range [11].

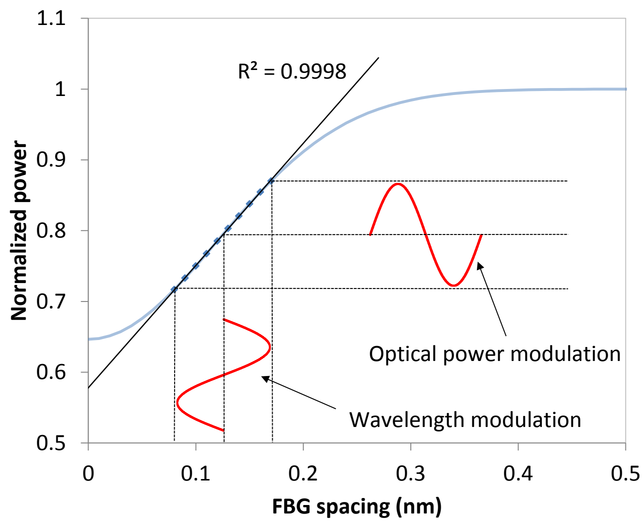

Fig. 4. Normalized optical power levels versus FBG spacing for two FBGs having equal bandwidths and reflections.

IV. Phase-Earth Fault Simulation

A number of different fault scenarios were investigated, of which only one representative example is presented below.

A phase-earth fault scenario for a 132 kV transmission line model, shown in Fig. 2, is considered. Assuming that the transmission line has an impedance of 200 Ω, the total fault current of 380 A can be expected. For the fault occurring in the center of the protected zone, the fault currents detected by the Rogowski coils at two ends of the protected zone will have approximately 190 A (269.44 A magnitude) and inverted phases.

At a primary current of 190 A (269.44 A_{pk}) the considered Rogowski coil will generate about 0.27 V_{pk} across the piezoelectric transducer as shown in Fig. 5. This voltage level will result in a Bragg wavelength shift of approximately 6 pm peak-to-peak, giving a power modulation of 1% of the maximum power based on the results presented in Fig. 4. The optical power modulation in response to the discussed fault scenario is presented in Fig. 6. By comparing changes in the optical power modulation with a set threshold, fault occurrence can be detected and a trip signal generated accordingly [11].

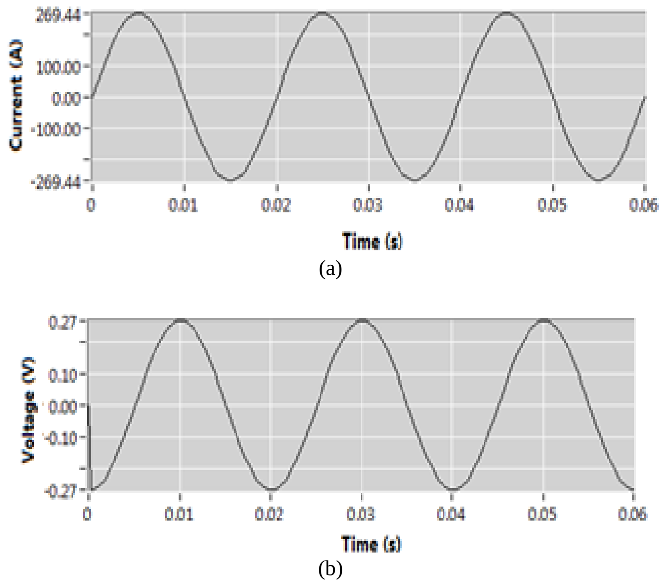

Fig. 5. Simulated Rogowski coil signals (a) primary (fault) current, (b) open circuit emf.

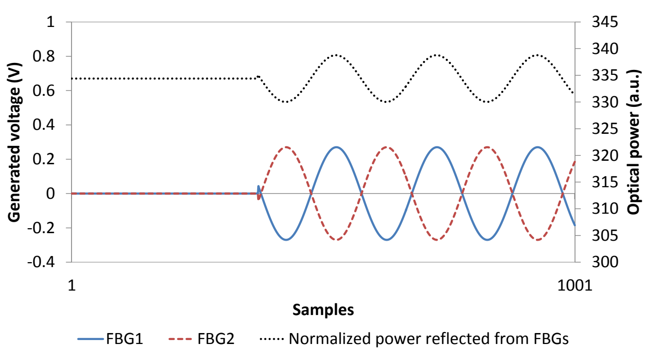

Fig. 6. Simulated sensors response to fault occurrence.

V. Discussion

Since the successful fault detection is dependent on the ability of the system to detect the optical power modulations, it is of great importance to ensure sufficient signal-to-noise ratio in the optical system. When the optical power modulation is small (as in this case), it might not be detectable without advanced signal processing techniques requiring not only increased computing power but also longer time for reaction to fault occurrence. Therefore, using low noise photodetectors and high power optical sources is crucial to achieve adequate performance of the proposed technique.

A 5-mW source with a 50-nm bandwidth has a 100 µW/nm optical power density. The maximum power reflected by two FBG sensors having 0.2 nm bandwidth equals to approximately 40 µW. Thus, at 1% power modulation, a 400 nW peak-to-peak power signal can be expected at the photodetector. Providing that a commercially available photodetector such as Optosci LNP-2 with a NEP of 15 $fW\cdot Hz^{-1/2}$ is used, a 1.5 pW noise power level can be expected at 10 kHz bandwidth. Since the optical power modulation is much higher than the noise level (SNR_{dB}=54dB), it can be concluded that the proposed system should be capable of fast-acting fault detection in real deployment, without resorting to complex signal extraction processes.

VI. Conclusion

In this paper, we have proposed and theoretically evaluated a novel approach to differential unit protection using two identical optical current sensors based on Rogowski coils, low voltage piezoelectric transducers, and fibre Bragg grating sensors. By monitoring the reflected optical power modulation and comparing it to a set threshold, faults can be detected. By evaluating various phase-earth fault scenarios through simulations we have shown that the new technique has the potential to enable very fast-acting and inexpensive all-optical unit protection.

It should be noted that the simulation results presented in the paper were achieved with neglected optical power attenuation due to the length and/or bending of addressing fibre. It was also assumed that the optical sensors were kept at the same temperature. Future work will concentrate on addressing these issues to assess their influence on the proposed system performance.

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