Optical Current Transducers for High Voltage Applications

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Abstract

In this paper we describe the fiber-optic current transformer being developed by NxtPhase. The technology, an offshoot of Honeywell's fiber optic gyroscope product, is targeted for applications in high voltage metering and protection applications.

Background

Over the past 15 years, optical current sensors have received significant attention by a number of research groups around the world as next generation high voltage measurement devices, with a view to replacing iron-core current transformers in the electric power industry. Optical current sensors bring the significant advantages that they are non-conductive and lightweight, which can allow for much simpler insulation and mounting designs. In addition, optical sensors do not exhibit hysteresis and provide a much larger dynamic range and frequency response than iron-core CTs.

A common theme of many of the optical current sensors is that they work on the principle of the Faraday effect. Current flowing in a conductor induces a magnetic field, which, through the Faraday effect, rotates the plane of polarization of the light traveling in a sensing path encircling the conductor. Ampere’s law guarantees that if the light is uniformly sensitive to magnetic field all along the sensing path, and the sensing path defines a closed loop, then the accumulated rotation of the plane of polarization of the light is directly proportional to the current flowing in the enclosed wire. The sensor is insensitive to all externally generated magnetic fields such as those created by currents flowing in nearby wires. A measurement of the polarization state rotation thus yields a measurement of the desired current.

The optical current transducer being developed by NxtPhase (the NXCT) is an offshoot from the Honeywell fiber optic gyro program. Honeywell has been producing fiber optic gyros for a variety of commercial aviation applications since 1992. Extensive life and reliability testing has been carried out on the product to meet the stringent flight qualification criteria. Early on, Honeywell realized that this technology, with only minor modifications, could be applied to the field of current sensing, and a program to diversify into this area was maintained by Honeywell for several years. In late 1999, Honeywell joined with Carmanah Engineering to launch NxtPhase with the charter of commercializing the technology.

Principle of Operation

The NXCT uses the Faraday effect, but in a different architecture than the more well known polarimetric technique. The NXCT is a fiber optic current sensor and it works on the principle that the magnetic field, rather than rotating a linearly polarized light wave, changes the velocities of circularly polarized light waves within a sensing fiber wound around the current carrying conductor [1]. The effect is the same Faraday effect but differently formulated. We have found in our experience and heritage from the Honeywell fiber-optic gyroscope program that, for a variety of reasons, it is easier to accurately measure changes in light velocity than changes in polarization state. Chief among these reasons is that by using a velocity measurement scheme, we do not need to construct the sensing region from annealed fiber which is brittle and difficult to work with in a production environment.

The optical circuit of the NXCT is shown in Figure 1. Light from an LED is launched into an optical fiber where it is polarized and then split into two orthogonally polarized light waves. These two waves travel down a polarization maintaining (PM) fiber to the sensing head. A fiber optic quarter-wave plate converts the two waves to right- and left-hand polarized light waves, respectively. These two waves then travel through the sensing fiber which is wound an integral number of times around the current carrying conductor. The two waves travel through the sensing fiber at different speeds, the difference being proportional to the strength of the magnetic field aligned with the sensing fiber. At the end of the sensing region, the two waves reflect off a mirror. Upon reflection, the sense of circular polarization of the two waves is swapped, and the two waves now travel in the opposite direction with respect to the magnetic field. These two changes counter-act, and the two waves continue to maintain their velocity difference for the return trip through the sensing fiber.

Once the light has retraced its way through the sensing region, the two waves again encounter the quarter-wave plate where they are converted back to linear polarization states. Now, the light that traveled outbound in the PM fiber as *x*-polarization returns in the *y*-polarization state, and vice-versa. The two beams are recombined in the polarizer and then diverted to a photo-detector. An analysis of the propagation paths of the two light waves reveals that they have traversed the same path, only in reverse order. One light wave traveled *x*-polarized outbound in the PM fiber, right-hand circular outbound in the sensing fiber, left-hand circular inbound in the sensing fiber, and finally *y*-polarized inbound in the PM fiber. The other light wave traveled *y*-polarized outbound in the PM fiber, left-hand circular outbound in the sensing fiber, right-hand circular inbound in the sensing fiber, and finally *x*-polarized inbound in the PM fiber. These two paths are reciprocal. The only physical quantity which affects the time-of-flight difference between the two light waves is the magnetic field acting on the sensing head through the Faraday effect. Thus, a measurement of the time-of-flight difference between the two waves yields an accurate measurement of the current flowing in the wire passing through the sensing head.

The time-of-flight difference to be measured is quite small; 10^{-21} to 10^{-15} seconds is the range for typical currents of 100 mA to 100 kA. However, these measurements are the standard fare of the fiber optic gyroscope community, and appropriate signal processing techniques can be borrowed from that field. In the NXCT, we are using electronics directly transferred from Honeywell's fiber gyroscope program. The basic idea is that the time-of-flight difference is measured as a phase shift between the two interfering light waves, and a modulator placed at the beginning of the PM fiber translates the phase shift information to a high frequency carrier. The signal at the photo-detector is digitally demodulated, and control signals are fed back to both the light source and the modulator. The output of the sensor is inherently digital; typically, the current flowing in the wire is described by a 16 bit word, updated every few microseconds. Noise averaging allows for > 20 bit resolution for frequencies below 1 kHz. A digital to analog converter is used to convert the digital output to a low-level analog output. If a high power analog output is required, a power amplifier is used.

Because the current information is impressed on a high frequency carrier (e.g., 320 kHz in today's prototypes), the frequency response of the sensor is limited by aliasing concerns. Our signal processing yields a frequency response equal to ¼ the carrier frequency, or about 80 kHz in our prototypes. The group delay of the sensor – the time it takes for an event in the current to show up in the sensor output – is 11.25 µs. The uncertainty in this delay is less than 100 ns, which corresponds to 0.13 minutes of phase uncertainty at 60 Hz.

Development/Product Plans

The NXCT physically divides into three separable elements as shown in Figure 2, the opto-electronics chassis, the fiber optic cabling, and the sensor head and standoff. The opto-electronics chassis contains all the electronics as well as the light source and optical components up through the modulator (see Figure. 1.). The opto-electronics chassis for a three-phase system, including the power supply, are designed to fit into a 19" 3U rack and would be in the control room. The fiber optic cabling – one PM fiber cable for each sensor – is connectorized at both ends so that the opto-electronics chassis and sensor head and standoff can be transported and serviced independently. Our first sensors are designed to accommodate up to 500 meter cable lengths. Longer cable lengths up to 1km are possible. The sensor head and insulator column is all dielectric and sufficiently light weight that it can be either supported by the line itself, or integrated into existing support structure.

Figure 3 shows temperature performance data of an early NXCT prototype. The peak scale factor deviation over the temperature range –40 to +60 deg. C is seen not to exceed ±0.2%. The RMS performance of the scale factor accuracy of this data is 0.025%. This performance has been achieved without the use of any explicit temperature measurement at the sensing head. This represents a significant improvement over our earlier prototype sensor fielded by Honeywell at Arizona Public Service's Cholla power generating station, which achieved 0.03% RMS performance over temperature, but with an explicit fiber optic temperature sensor mounted along side the sensing head [2]. We overcame the need for an explicit temperature sensor by using the fact that the quarter-wave plate within the sensing head changes predictably with temperature and gives information recoverable from the modulated waveform received at the photo-detector that depends only on the temperature. The data in Figure 3 has been characterized using this recovered temperature information.

One interesting feature of the fiber current sensor is that the dynamic range of the sensor can be scaled to fit almost any application, simply by changing the number of fiber turns on the sensor head. Our first prototypes use four turns of sensing fiber, which allows the sensor to reliably detect currents over the range 100 mA to 100 kA. This range covers the vast majority of high voltage metering and relaying applications requirements. We have also built one turn sensing coils, which reliably measure currents over the range 400 mA to 400 kA. We envision such a device being used as a portable clamp-on sensor, perhaps as an in situ calibration instrument. We have also built sensors with as many as 550 fiber turns. These sensors proved to be able to reliably detect currents below 100 µA in a single wire passing through the sensor and were successfully used to distinguish displacement currents and leakage currents in a conductor. In one proof of concept experiment, we also wrapped 1500 turns of wire around a 550 fiber turn sensor and demonstrated reliable detection of currents below 100 nA. This level of flexibility in a fiber current sensor allows us to increase the sensitivity up to a million times over the level required for traditional metering and protection applications. New classes of applications in condition monitoring become possible.

From a practical standpoint in conventional applications, a single NXCT with a 1000 A rated current, can be used for 0.3% class metering with 100,000 A short circuit current measurement capability for protection.

The next step in proving the NXCT prior to commercial product availability is a field trial. The next field trial is planned for April at BC Hydro's Ingledow substation in a three phase 230 kV installation. The NXCT will be deployed with the NXVT Optical Voltage Transducer as a combined current and voltage sensor.

The units will be integrated with two power meters demonstrating interfaces for both high energy as well low energy analog outputs in conjunction with a data acquisition system for advanced waveform capture.

Conclusion

In conclusion, we believe the NXCT fiber current sensor will meet or exceed the most demanding high voltage metering and relaying applications specifications. Considerable flexibility exists for tailoring the number of fiber turns on the sensing head to center the current sensing range around the customer’s desires. Initial product efforts are targeted for both metering and relaying applications. The NXCT design has evolved from the first prototypes delivered by Honeywell in 1997, which in turn were a short design step away from the base-line fiber optic gyroscope in production at Honeywell for commercial airline applications since 1991.

References

[1] J. Blake, “Current sensors based on the Sagnac interferometer,” *invited paper*, Proc. of the SPIE, Fiber-optic and laser sensors XIV, 166-171 (1996)

[2] K. Stalsberg, W. Au, L. Stranjord, T. El-Waily, R. Goettsche, G. Sanders, J. Blake, J. Demko, W. Chilton, “Fiber optic current sensor and multi-application data acquisition and analysis system”, Proceedings of the Georgia Tech Fault and Disturbance Analysis Conference (1998)

Figures

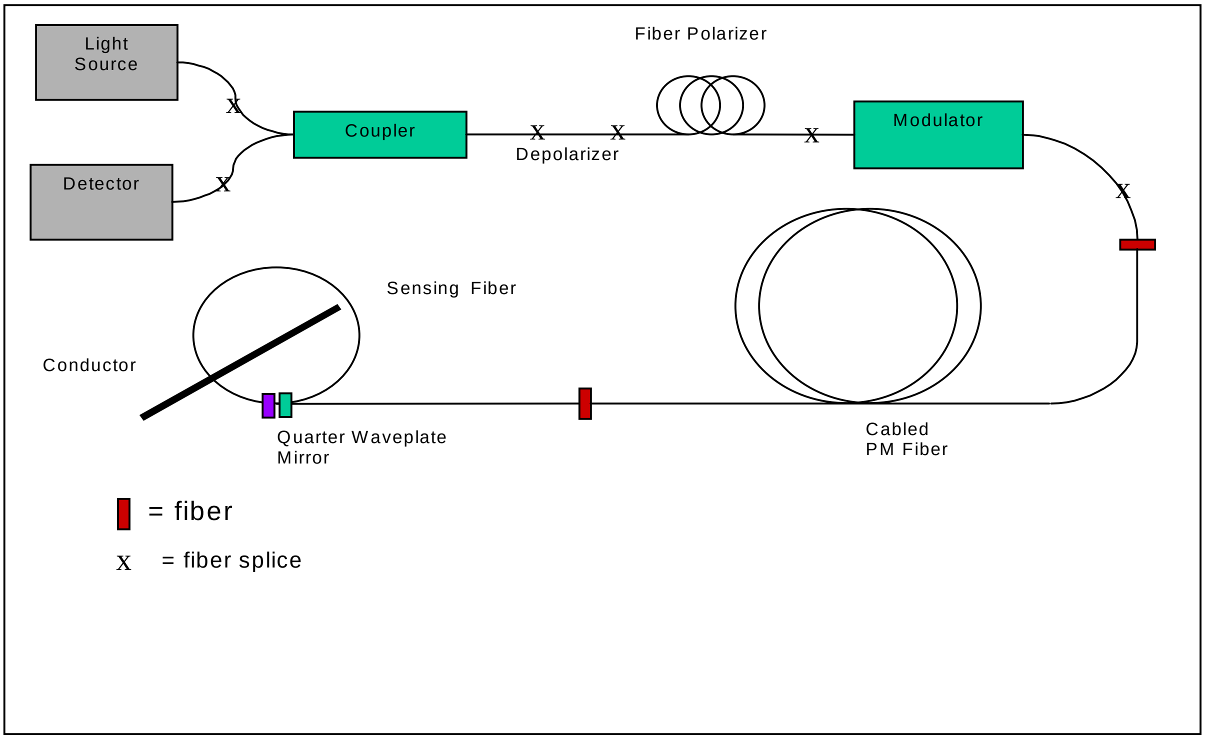

Figure 1: NXCT Optical Circuit

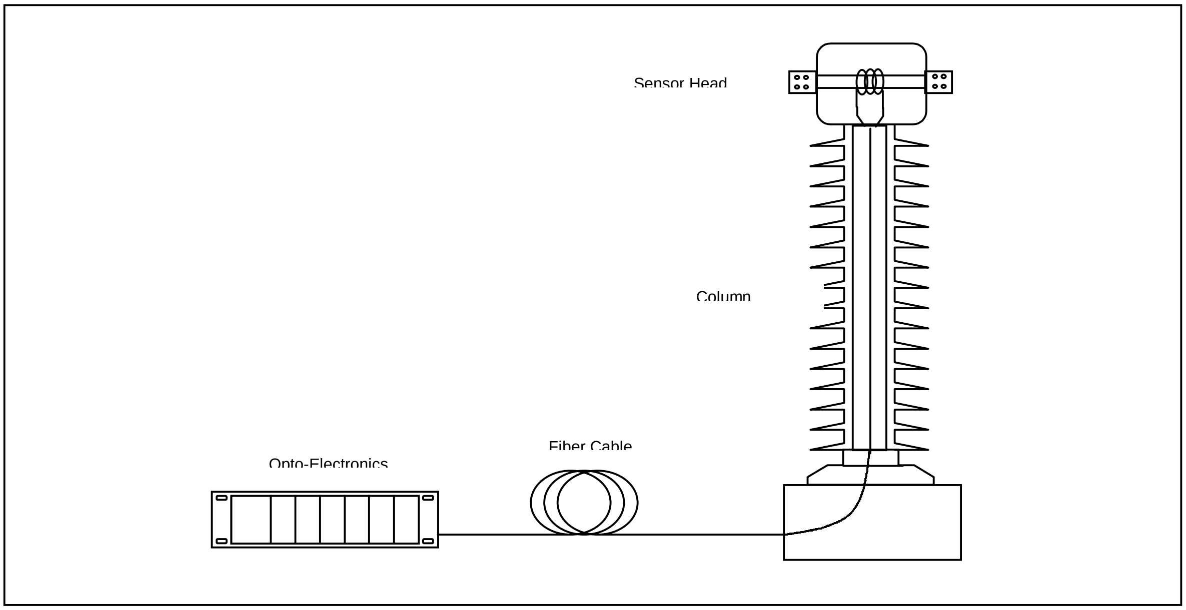

Figure 2: NXCT Optical Current Transducer

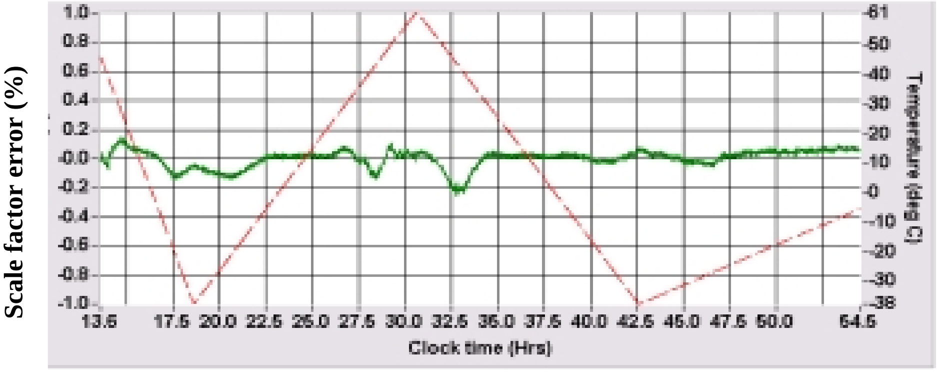

Figure 3: NXCT scale factor error over temperature