The InterNational Electrical Testing Association Journal

FALL 2018

NETA WORLD™

www.netaworld.org

EMERGING TECHNOLOGIES

Latest Developments in Online Partial Discharge Diagnosis

CONTINUOUS MONITORING IS ON THE RISE PAGE 48

THE PAST AND FUTURE OF FIBER OPTICS IN UTILITIES PAGE 56

ISSN 2167-3594 NETA WORLD JOURNAL PRINT
ISSN 2167-3586 NETA WORLD JOURNAL ONLINE

NON-CONVENTIONAL INSTRUMENT TRANSFORMER DESIGNS FOR AIR INSULATED SUBSTATIONS

BY STEVEN A. KUNSMAN, NICHOLAS POWERS, and BHARADWAJ VASUDEVAN, *ABB Inc., USA*

In today's electrical systems, currents in high-voltage equipment are measured using bulky and heavy current transformers in oil- or SF_6-insulated designs. These use the principle of electromagnetic induction to generate a small secondary current, typically 5A or 1A nominal at rated current, from a primary current, which then serves as an input for protection relays or energy meters. Such transformers have represented the state of the art for many decades, and they operate reliably under the harsh conditions found in an outdoor substation.

However, besides their size and weight, these transformers have a number of additional shortcomings, the most important of which is that, as a result of magnetic saturation and limited bandwidth, the waveform of the secondary current is often not a true image of the primary current. Over 40 years ago, it was recognized that the Faraday Effect could be the basis of a new and better, technology for current measurement. But it is only in the last 20 years that appropriate technology has become sufficiently mature to allow it to be used as a commercially attractive basis for fiber optic current sensor (FOCS) applications. The remarkable progress made by the optical communications business has provided many components that can be re-used for the FOCS, including light sources, fiber-optics, modulators, and photodetectors.

Optical current and voltage sensors have found significant interest in recent years for use in electric power transmission. In particular, fiber-optic current sensors have become rather mature and are finding commercial applications not only in high-voltage systems, but also in industry, e.g., in the measurement of high direct currents (dc) in the electro-winning of metals (aluminum, copper, etc.). Optical sensors offer considerable benefits over conventional instrument transformers. They are inherently free of magnetic saturation and typically have a measurement bandwidth in the range of kilohertz (determined by the data rate). Bandwidths in the range of tens or hundreds of kHz are also feasible. As a result, fiber-optic current transformers deliver a true image of the primary current within their measurement range, and can also be used for fast-transient currents, short-circuit currents, and alternating current (ac) with dc offset. Furthermore, optical CTs are lightweight and small. It is possible to operate them as freestanding devices or integrate them easily into other power products. Substation footprint and installation costs are reduced. Other advantages include enhanced safety (no risk from open secondary CT circuits or catastrophic failure) and environmental friendliness (no oil). Optical current sensors are immediately compatible with modern digital substation communication, which helps to eliminate large amounts of copper cabling.

Modern fiber-optic current sensors have been developed for use in electric power transmission as well as for the measurement of high dc in industrial applications. Fiber optic current sensors use light to deduce the precise magnitude of current that is creating the magnetic field. FOCS designs for high-voltage substations include FOCS integrated with DCB disconnecting circuit breakers (DCBs), FOCS kits for integrating with other high-voltage equipment such as gas-insulated switchgear and generator circuit breakers, and free-standing fiber optic current sensors (FOCS-FS). The major difference is that these modern sensors now provide direct-to-digital outputs, not the analog outputs offered by earlier designs.

420kV Oil-Filled Current Transformers

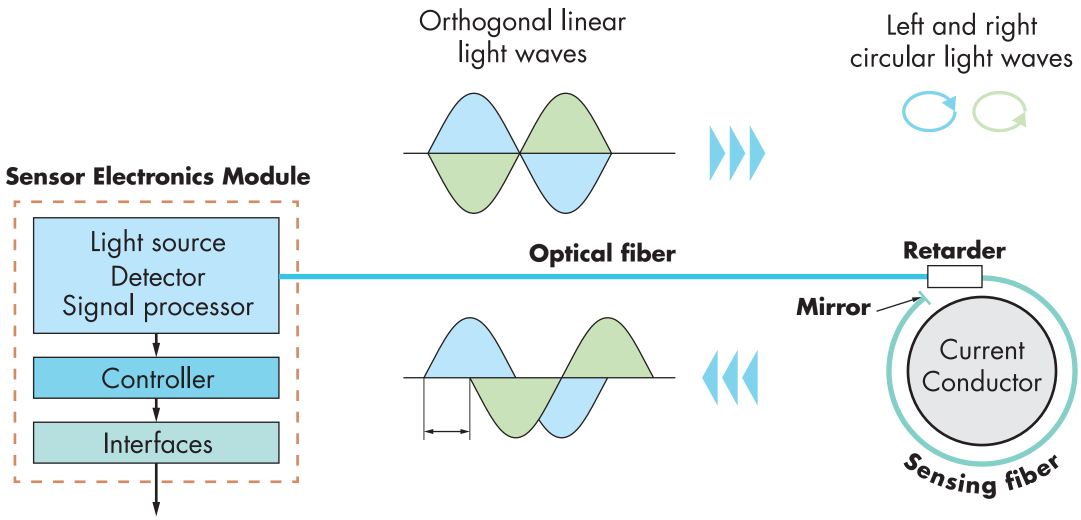

Figure 1: *FOCS Configuration*

FOCS DESIGN AND HOW IT WORKS

FOCS designs exploit the Faraday Effect, which defines that left and right circularly polarized waves propagate at slightly different speeds when they travel in a medium that is subject to a magnetic field. The main components of the FOCS are an optoelectronics (OE) module or sensor electronics module at ground potential and a coil of sensing fiber, which is wound around the current conductor (Figure 1)

The OE module includes a semiconductor light source and a closed-loop detection circuit with a fiber-optic polarizer, an optical phase modulator, and a digital signal processor. The module sends two light waves with orthogonal linear polarization to the sensing fiber coil. At the coil entrance, a fiber-optic polarization converter transforms the linear waves into left and right circularly polarized light waves. These waves travel at different speeds through the sensing fiber in the magnetic field (caused by the current) as a result of the Faraday Effect, and this in turn creates an optical phase difference. The waves are reflected at the end of the fiber and they retrace their optical path back to the optoelectronics module, where they interfere at the polarizer.

The signal that results from the interference depends on the phase difference and is measured by a photodiode. The closed-loop control circuit reverses the current-induced phase shift by means of a phase modulator so that the phase difference of the waves when they interfere at the polarizer is always kept at zero. The feedback signal to the modulator is then essentially an image of the primary current and the digital sensor output is derived from this signal. A particular advantage of this closed-loop detection scheme is that the signal is perfectly in proportion to the primary current over the entire measurement range. The roundtrip phase difference of the two light waves is proportional to the number of fiber loops and the line integral of the magnetic field along the closed path described by the sensing fiber. Geometrical parameters such as the coil diameter or the position of the conductor inside the fiber coil do not affect the signal. Currents outside the coil also have no influence.

Operation of the sensing fiber in reflection mode has the advantage that the sensor becomes immune to mechanical disturbances. The mirrored coil end swaps the polarization states of the light waves. As a result, vibration-induced phase shifts cancel each other out over one roundtrip of the waves while the non-reciprocal magneto-optic phase shifts double.

By appropriately selecting the number of fiber loops, the measurement range can be optimized for specific applications. The typical sensor as made for power transmission applications has a range of ±180kA. The operating temperature range of the sensor head is from below -40 °C to 105 °C. The OE module is designed for operation in a heated outdoor cubicle. It can be operated with three fiber coils in parallel to cover all three phases normally found in a high-voltage installation.

ASCERTAINING ACCURACY AND STABILITY

The FOCS system is designed to meet the requirements for metering and protection in electric power transmission systems according to IEEE Class 0.15s, IEC Class 0.2s, Class 5P, and Class 5TPE. To achieve such performance, it is essential that the circular polarization states of the light waves in the fiber coil are well maintained under all conditions of operation and not disturbed, e.g., by mechanical stress acting on the fiber. Furthermore, the temperature dependence of the Faraday Effect (0.7 percent per 100 degrees C) must be taken into account. Techniques have been developed to package the sensing fiber in a stress-free manner and to inherently compensate for the variation of the Faraday Effect from temperature by means of the fiber retarder, which generates the circular light waves. Figure 2 and Figure 3 graphically represent the method of the temperature compensation.

The polarization converter (fiber retarder) at the entrance to the fiber coil converts the two linearly polarized light waves coming from the opto-electronics module into left and right circularly polarized waves before the light enters the fiber coil. The scale factor (sensitivity to current) of the sensor varies with the phase retardation ρ introduced by the polarization converter in a parabolic manner illustrated in Figure 2.

The red heavy curve segment indicates the scale factor decreasing at increasing retarder temperature, which balances the opposite change of the Faraday Effect with temperature.

If the room temperature retardation of the polarization converter is set to about 100 degrees instead of 90 degrees, the scale factor decreases at rising temperature stemming from the retarder (along the red heavy curve segment shown in Figure 2) and just balances the increase in the Faraday Effect as shown in Figure 3.

The theoretical scale factor versus temperature curve is calculated neglecting bend-induced birefringence in the fiber coil. Some modifications apply in case of non-negligible birefringence.

With these measures, the sensor output becomes independent of temperature well

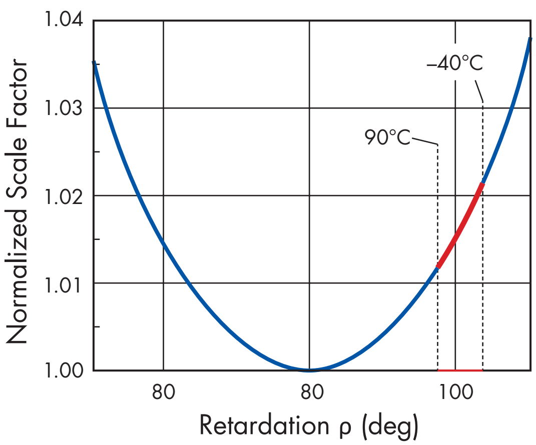

Figure 2: *Sensitivity to Current*

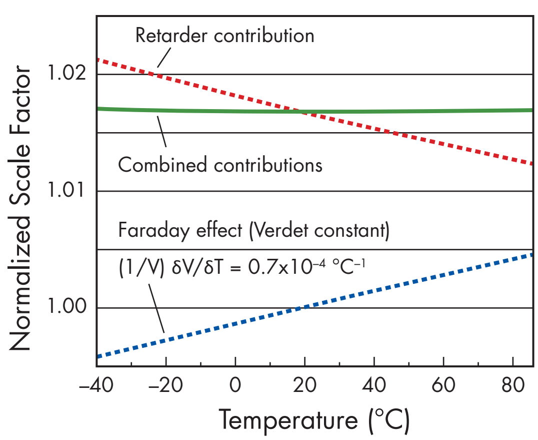

Figure 3: *Scale Factor Balanced by Temperature*

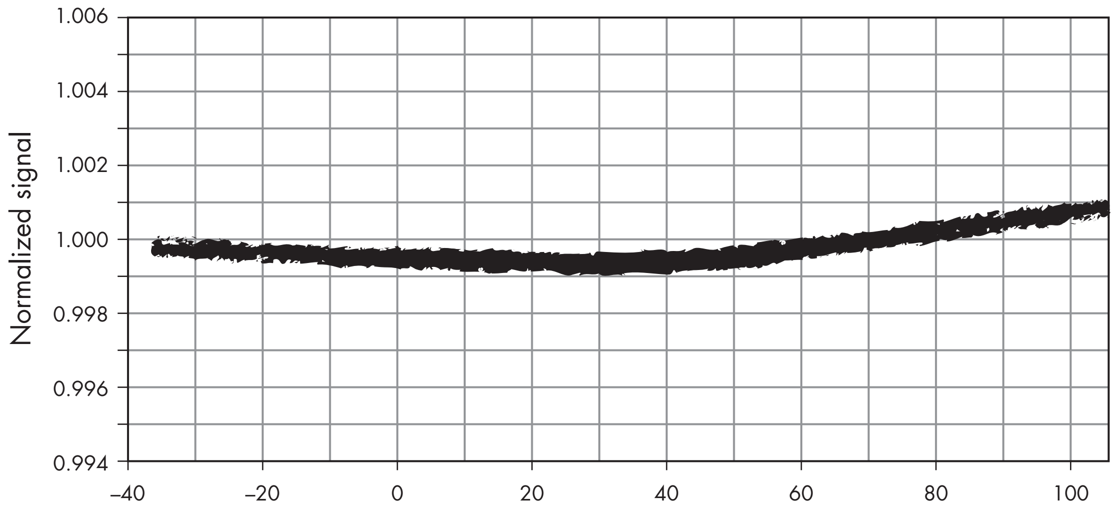

Figure 4: *Sensor Output*

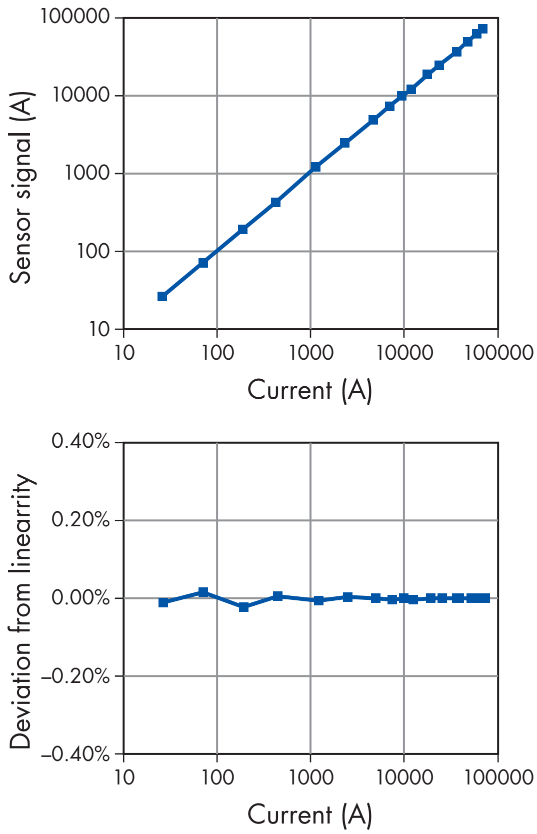

Figure 5: *Linear Relationship of FOCS Signal to Applied Current*

less than ±0.1 percent over a range of at least from -40 to 85 degrees C without the need of an extra temperature compensation using additional T-measurement (Figure 4). Even at 105 degrees C, the sensor coil is still within the requirements of IEEE metering class 0.15 and IEC metering class 0.2.

The physical principle and the proper choice of materials, coupled with absence of any non-linear effects, defines excellent predictability and the perfectly linear relationship of the FOCS signal to the applied current, as shown in Figure 5.

FOCS overall system accuracy is independent on the measurement current range, so the same sensor can be designed and used for protection and measuring in the whole dynamic range of common power devices. Further on, the system measures only the instantaneous values of a current; more precisely, it is measured average current during 700-800 nanoseconds without any effects of the current history curve. Therefore, the same system can be used for measurement of ac and dc currents, as well as for ac with dc offset.

MEASURING DIRECT CURRENT FROM GEOMAGENTIC DISTURBANCES

The fiber optic current sensor was originally designed to measure direct current. Applications included current measurement for process control and protection in the electrowinning industry, for example at

Figure 6: *GMD Produced from Solar Flares*

aluminum smelters. The ability to measure direct current (dc) is very important for transmission utility alternating current (ac) application. The North American Reliability Corporation (NERC) has introduced TPL-007, which requires bulk power transmission and generation owners to monitor the effects of geomagnetic disturbances (GMDs). The disturbances, a result of our sun's solar flare activity, produce geomagnetic induced currents (GICs) coupling to utility transmission lines.

During a GMD event, the GIC into the transmission line could impact the large power transformer because the dc coupled with the GIC causes the transformer to have hot-spot heating that leads to damage. These loose, reactive power sources increase the reactive power demand, which may lead to system voltage collapse and potential blackouts.

NERC TPL-007 requires asset owners to perform vulnerability assessments of their system to be able to a benchmark a "1-in-100-year" GMD event. One common solution to address this measurement is to apply Hall-effect sensors to the neutral on large power transformers at risk. However, the neutral dc measurement does not represent the actual transmission line direct current and is inadequate for autotransformers.

Deployment of the FOCS will allow a precise measurement of both the ac and dc measurements on the transmission line per-phase currents. The extraction of the per-phase dc line current can be used to not only measure the amount of line current, but also drive an automated mitigation scheme that assesses transformer impact and identifies the required reactive power to stabilize the impacted large power transformer. The combination of the FOCS and a modern substation protection and control device measures and extracts the dc value that is delivered to the utility operation center via a SCADA protocol or pay loaded into the synchrophasor measurement unit (PMU) data for proactive mitigation or long-term profiling.

Figure 7: *This large power transformer could be impacted by GMDs produced from solar flares.*

LOOKING AHEAD

FOCS technology will serve as a platform for other high-voltage applications. The variable diameter of the sensing head allows the sensor to be easily adapted to high-voltage equipment such as gas-insulated switchgear (GIS) or generator circuit breakers. By choosing the fiber loop number appropriately, high accuracy can also be achieved at low currents, e.g,. in zero sequence current measurements. New or improved substation protection and monitoring functions may follow from the fast response of the FOCS and its precise measurement of both ac and transient dc.

Using FOCS in high-voltage substations means the measurement is digitized right at the source and transmitted as a digital signal, via the process bus, to the protection and control IEDs, as well as the revenue meters. This eliminates copper runs from the substation back to the control room. Coupling the benefits of fiber-optic current sensor solution with direct-to-digital capability will facilitate the development of digital substations and enable the grid to get smarter. New FOCS designs address demanding performance requirements for accuracy across a wide temperature range. It is inherently free of magnetic saturation, making it ideal for capturing fast-transient currents and short-circuit currents. The compact design helps achieve reduced substation footprint, as it requires much smaller space compared to conventional instrument transformers. It is also an eco-efficient solution that uses no oil or gas, eliminating the risk of explosion.

CONCLUSION

FOCS is one of a range of unconventional instrument transformers (NCITs) that can make substations entirely digital. These NCITs have to be every bit as reliable as the equipment being replaced — and they are. Over the past 30 years of real work experience, companies making optical sensors have gained a unique perspective of how to make these systems more reliable. Extensive use of NCITs makes a substation simpler, cheaper, smaller, and more efficient. Improvement in fiber-optic current sensors and integration of standalone merging units also provides utilities and engineering firms with a great tool box for the future deployment of this maturing technology. For retrofit applications, the possibility of installing the new process bus system in parallel with the existing system will allow the substation to remain in service during the main part of the work. This will be a big advantage, reducing outages to a minimum during the retrofit.

REFERENCES

K. Bohnert, P. Gabus, H. Brändle, and A. Khan. "Fiber-optic current and voltage sensors for high-voltage substations," 16th International Conference on Optical Fiber Sensors, Nara, Japan, October 13-17, 2003, *Technical Digest*, pp 752-755.

Rahmatian, G. Polovick, B. Hughes, and V. Aresteanu. "Field experience with high voltage combined optical voltage and current transducer," Cigre (Paris), Session 2004, paper A3-111.

J. Wang, Z. Guo, G. Zhang. "Study on long-term stability of 110 kV power optical sensor solution - optical current transducer," in Proceedings APPEEC 2010 (Asia-Pacific Power & Energy Engineering Conference 2010), Chengdu, China, 28-31 March 2010, pp 1178-1179.

K. Bohnert, P. Gabus, J. Nehring, H. Brändle, M. Brunzel. "Fiber-optic high current sensor for electrowinning of metals," *Journal of Lightwave Technology*, 25(11), 3602 (2007). 5. German patent E4224190B4, 22.7.1992.

Frosio and R. Dändliker. "Reciprocal reflection interferometer for a fiber-optic Faraday current sensor," *Appl. Opt.*, vol. 33, no. 25, pp. 6111-6122, 1994.

J. Blake, P. Tantaswadi, and R.T. de Carvalho. "In-line Sagnac interferometer current sensor," IEEE Trans. *Power Delivery*, vol. 11, no. 1, pp. 116-121 (1996).

K. Bohnert, P. Gabus, J. Nehring, and H. Brändle. "Temperature and vibration insensitive fiber-optic current sensor," *Journal of Lightwave Technology*, 20, 267-276 (2002).

H-E Olovsson, T. Werner, P Rietmann. "Next generation substations," ABB Review Special Report on IEC 61850, pp. 33-37

***Steven A. Kunsman** is Director Product Management and Applications, ABB Power Grids - Grid Automation North America. Steve joined ABB Inc. in 1984 and has over 34 years of experience in substation automation, protection, and control. He graduated from Lafayette College with a BS in Electrical Engineering and from Lehigh University with an MBA concentrated in management of technology. Today, Steve is responsible for ABB North American Substation Automation business' technical team. He is an active member of the IEEE Power Engineering Society PSRC and PSCC Committees, PSCC Cyber Security Subcommittee chair, and has held multiple working group chairs, an IEC TC57 US delegate in the development of the IEC61850 communication standard, and UCA International Users Group Executive Committee Co-Chair..*

***Nicholas Powers** is NAM Marketing Manager, ABB Power Products — High Voltage Instrument Transformers. Nick joined ABB in 2008 with the acquisition of Kuhlman Electric and is ABB's NAM HVIT Marketing Manager and Global Product Marketing Manager for Station Service Voltage Transformers. He has 37 years of experience in the instrument transformer field for electrical systems from 600 V up to 800 kV. Nick has a B.S. in electrical engineering from the University of Kentucky and completed courses of study in marketing and business development at the University of Wisconsin School of Business. He has helped develop advanced HVIT designs targeted for the rapidly changing electric utility in measurement, protection, and control instrument transformer needs.*

***Bharadwaj Vasudevan** is an Application Engineer at ABB Power Systems — Substation Automation North America. He graduated from North Carolina State University with an M.S. in electrical engineering and started his career with Areva T&D Ltd in New Delhi, India, as a Power Systems Engineer. Bharadwaj worked on various EHV substation design projects throughout India before joining ABB as a consulting engineer for the Power Systems group. With a strong background in real-time power system modeling, he develops transient system models for transmission planning projects. In his current role with the Power Systems Automation group for the North America market, he supports all transmission-level Relion relay products from Raleigh, North Carolina. He is a member of the IEEE Power System Relay Committee and contributes to various working groups in the Relay Communications subcommittees.*