Invited paper at 16th International Conference on Optical Fiber Sensors, October 13-17, 2003, Nara Japan
Technical Digest, pp 752-754.

Fiber-Optic Current and Voltage Sensors for High-Voltage Substations

K. Bohnert, P. Gabus, and H. Brändle

ABB Switzerland Ltd, Corporate Research, CH-5405 Baden-Dättwil, Switzerland
Phone: +41 58 586 8044, Fax: +41 58 586 7358, E-mail: klaus.bohnert@ch.abb.com

Aftab Khan
ABB Inc, 100 Distribution Circle, Mount Pleasant, PA 15666, USA

ABSTRACT

We report on ABB's fiber-optic current and voltage transducers and their applications in high-voltage substations. We consider bulk-optics and all-fiber current sensors and voltage sensors that exploit the electro-optic effect in BGO and the piezo-electric effect in quartz.

1. INTRODUCTION

In recent years optical current and voltage transducers have reached a high degree of maturity and started to compete with conventional instrument transformers. Fiber-optic transducers are ideally adapted to high-voltage environments as they are highly immune to electro-magnetic interference and there is no galvanic connection between the sensor head on high-voltage and substation electronics. Many problems of their conventional counterparts are inexistent such as magnetic saturation or danger of catastrophic failure. The wide bandwidth of optical sensors is important for fast protection and power quality monitoring. Optical transducers can be easily installed on or integrated into existing substation equipment such as circuit breakers or bushings resulting in significant space savings and reduced installation costs. Furthermore, there is no danger of a contamination of the environment due to loss of oil. In the following, we will consider optical current and voltage sensors that have been developed at ABB and examples of their applications.

2. CURRENT TRANSDUCERS

a) Bulk-Optics Current Transducer

ABB's first generation magneto-optic current transducer (MOCT) with more than 10 years of field experience exploits the Faraday effect in a block of fused silica glass with a central aperture for the current conductor[1]. The polarization-rotation of the transmitted light is detected after a single pass around the conductor. The glass body is thermally annealed to eliminate stress-induced birefringence. Multimode fibers with a 200 μm core diameter guide the light from the LED source to the sensor block and back to the detector. The sensor is mainly used for revenue metering over a primary current range from 3150 A to less than 5 A and reaches accuracy according to IEC class 0.2. For applications requiring particular immunity to shock and vibration a sensor version with two counter-propagating beams has been developed. Subtracting the two corresponding outputs doubles the current-induced signal while any reciprocal modulation due to mechanical effects is largely cancelled.

b) All-Fiber Current Transducer

More recently, also an all-fiber current sensor has been developed[2]. In comparison to the bulk-optics transducer it offers more flexibility in its design and applications as well as improved performance. Two configurations of the sensor have been investigated and compared. The first one is a Sagnac interferometer[3,4]. The magnetic field of the current produces a differential phase shift between two circular light waves counter-propagating in a coil of sensing fiber. In the second configuration the coil is operated in reflection[5-7]. Here, the phase shift is introduced between two co-propagating left and right circular waves that are reflected at the coil end and then retrace the optical path with swapped polarizations. The circular waves are generated at the coil entrance port(s) from linear waves by means of a short section of elliptical-core fiber acting as a phase retarder. Upon leaving the coil the circular waves are converted back to linear light. The relative current-induced phase shift of the returning linear waves is measured with an appropriately adapted fiber gyroscope module, which also provides the light source. A focus of the development was to achieve insensitivity to temperature and vibration. Commonly, uncontrolled mechanical stress in the sensing fiber is a main cause of drift in scale factor with temperature. The sensing fiber is thermally annealed to remove bend-induced stress[8] and resides in a thin capillary of fused silica. The capillary prevents any stress from packaging. The coiled capillary is embedded in a soft polymer in a ring-shaped housing (a photograph is shown in Fig. 1). The temperature dependence of the Faraday effect (0.7x10^{-4}/°C) is intrinsically compensated by the temperature dependence of the retarder(s). In the reflective sensor and certain configurations of the Sagnac sensor the scale factor varies with the square of the deviation of the retarders from perfect quarter-wave retardation[6,9]. Hence, the sensor can be designed such that the temperature dependences of the retarder(s) and the Faraday effect just cancel each other[2]. The degree of temperature compensation is controlled in situ during sensor manufacturing. Insensitivity to temperature within <0.2 % has been demonstrated between –35 and 85°C. An experimental comparison of the shock and vibration sensitivity of the two sensor configurations shows high immunity of the reflective sensor to mechanical effects. As a result of the polarization swapping at the reflector the already relatively small disturbances of the differential optical phase during forward propagation are largely cancelled on the return path.

As an example for a practical application Fig. 1 shows SF_6 gas insulated 170 kV circuit breakers with integrated fiber-optic current sensors in a substation near Pavia, Italy. The fiber coil housing is at the bottom of the breaker mechanism (arrow) in the gap between the current-carrying bus bar and the composite insulator of the breaker. The savings in substation space as a result of the sensor integration are obvious.

3. VOLTAGE TRANSDUCERS

a) Electro-Optic Voltage Transducer

The electro-optic voltage transducer (EOVT) exploits the Pockels effect in a cylinder-shaped BGO crystal ($Bi_4Ge_3O_{12}$), which has cubic crystal symmetry. The full voltage is applied between the two end faces of the crystal. The light double-passes the electro-optic material. At voltages in the several 100 kV range the field-induced birefringence causes a differential optical phase shift between two orthogonal polarizations corresponding to several wave periods. The waveform of the applied voltage is unambiguously reconstructed from two output signals in quadrature. The crystal orientation (cylinder axis along a [1,0,0]-direction) is such that only the field components parallel to the light path give rise to an electro-optic phase shift. Hence, the sensor measures the line integral of the field and is insensitive to external perturbations of the field distribution or to fields from neighbouring electric phases.

The assembly is operated in an SF_6 atmosphere contained in a composite insulator with silicone rubber sheds (Fig. 2). EOVTs for line voltages between 115 and 550 kV have been type tested in accordance with IEEE Standard 4. An additional temperature sensor is employed to compensate the temperature dependence of the Pockels effect (1.54x10^{-4} °C^{-1}). The transducers meet the accuracy requirements of class 0.2 for metering as defined in IEC and are used as an input to electronic metering and / or relaying systems.

An optical metering unit (OMU) combines optical current and voltage transducers (MOCT and EOVT) in a light-weight and compact single-phase unit (Fig. 2). The reduced size and increased accuracy of the OMU compared to conventional oil-filled current and voltage transformers make the design particularly well suited for the addition of revenue metering to existing substations where extra space may be scarce. These advantages are a good match to the growing deregulation-driven needs to retrofit extra-high-voltage substations with metering instrument transformers (Fig. 3).

b) Piezo-Optic Voltage Transducer

The sensor exploits the converse piezoelectric effect in a cylinder-shaped quartz transducer[10]. The periodic piezoelectric deformation of the transducer that is produced by an applied ac-voltage is sensed by an elliptical-core dual-mode fiber wound on the circumferential surface (see Fig. 4 for a photograph). The resulting modulation of the differential optical phase of the two spatial fiber modes (LP_{01} and even LP_{11} modes) is remotely detected by low coherence interferometry. The light source is a low coherent multi-mode laser diode. A second dual-mode fiber that is part of the detection system acts as a receiving interferometer. The two modes are incoherent at the end of the sensor fiber but again partially coherent at the end of the receiver fiber. Polarization maintaining single-mode fibers serve to transmit the light from the source to the sensing fiber and back to the detection system. The phase modulation is recovered by homodyne phase tracking with the phase tracker acting on the receiver fiber. The temperature dependence of the group delay in the sensor fiber and its effect on the fringe visibility is employed to determine the transducer temperature with a precision of about ±5-10 °C[11]. This is sufficient to compensate the variation of the piezoelectric effect with temperature (-2x10^{-4} °C^{-1}) without the need of an extra temperature sensor. With the proper crystal orientation (two-fold axis parallel to longitudinal transducer axis) the sensor also measures the line integral of the electric field.

Fig. 4 shows a transducer for 170 kV gas-insulated switchgear (GIS)[12]. The transducer housing is a compact device that can be plugged into an accordingly prepared GIS system. The main components are a base flange at ground potential and a high-voltage electrode separated by an insulator tube. The 100 mm long quartz crystal is mounted inside the insulator tube and experiences the full GIS voltage. The interior of the housing is in gas exchange with the GIS system with a chemical barrier for potential SF_6 decomposition products. Furthermore, a 420 kV prototype sensor for outdoor applications has been investigated[13]. Here, the voltage is divided among a series four 15 cm long quartz crystals. The crystals are interrogated with a common dual-mode sensor fiber. The detected phase modulation is proportional to the total voltage. As the voltage is distributed on several crystals the peak fields in the vicinity of the crystals are reduced. As a result, the quartzes can be housed in a rather slender and thus relatively low cost composite insulator. The insulator is filled with a soft polyurethane resin. The solid-state insulation eliminates the need of SF_6 gas and monitoring of gas pressure.

4. CONCLUSIONS

The development of fiber-optic current and voltage transducers and their practical applications in high-voltage substations have made noticeable progress in recent years. It is obvious that the new technology has important advantages over conventional instruments. Presently, the market share of optical systems is still low, however. Continuing efforts will be necessary to demonstrate the long-term reliability and further improve the acceptance and confidence in the new technology. Another critical challenge is the interface with end devices including meters and relays, as the signals of the optical transducers are vastly different from the outputs of conventional instruments. Also economic volume production needs to be organized.

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Fig. 1. 170 kV circuit breakers with integrated fiber-optic current transducers.

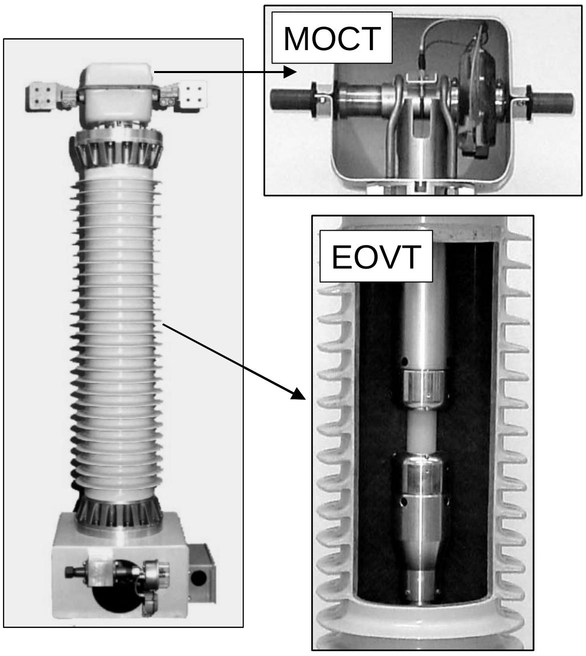

Fig. 2. Optical metering unit (OMU) with current transducer (MOCT) and voltage transducer (EOVT).

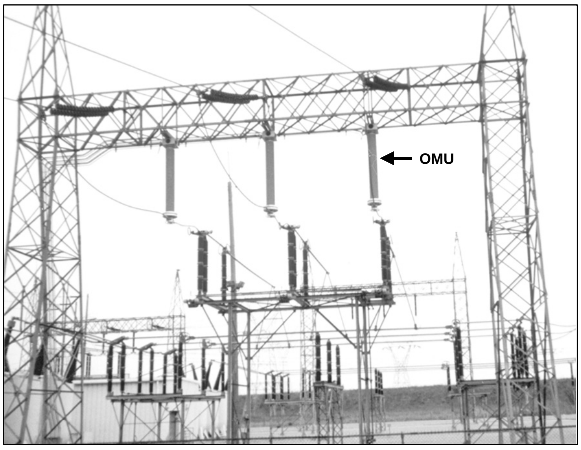

Fig. 3. OMU retrofit installation in a high-voltage substation in an inverted orientation on an existing line entrance tower.

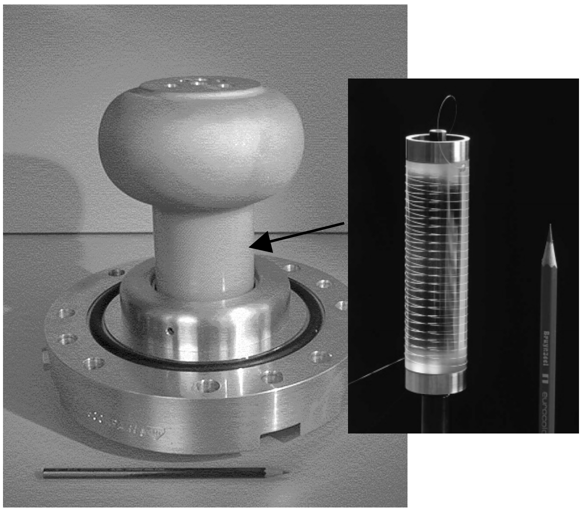

Fig. 4. Piezo-optic voltage transducer for 170 kV gas-insulated switchgear. The 100 mm long quartz crystal (right) is mounted inside a insulator tube (arrow) separating the high-voltage electrode (top) and the base flange at ground potential (bottom).