Interfacing Optical CTs and VTs to Relays and Meters

J. N. Blake, and A. H. Rose, *member*, *IEEE-LEOS*

***Abstract*—We demonstrate three different types of secondary interfaces with optical current and voltage sensors: digital, low-energy analog, and high-energy analog. We compare the merits and limitations of each type of output. In all cases the digital output is superior to the analog due to inaccuracies in the converters and amplifier limits. In some cases the digital optical output has accuracies equivalent to a transfer standard.**

***Index Terms*--current measurement, voltage measurement, optical fiber devices, power measurement, digital measurement.**

I. Introduction

LEGACY conventional current and voltage transducers (CTs and VTs), typically have fixed outputs of 5 A at rated primary current for CTs and 69 V or 115 V at rated primary voltage for VTs, according to IEC and IEEE standards. Secondary power meters, relays and recorders all have inputs that receive this high power. With the acceptance of microprocessor-driven secondary equipment, the natural question arises, why not have complete digital signal processing? However, conventional CTs' and VTs' high power secondary cannot be easily nor cost effectively rendered digital. Thus, because of market and technological barriers, very few meters and relays have been produced with digital inputs.

Over the last several decades technological development and improvements in optical sensors and Rogowski coil sensors have brought new power sensors to the utility market. However, they have not been widely accepted because the technologies were unproven, their secondary output was not high power, and there were few meters or relays available with which to interface. Thus, a market barrier exists for optical and Rogowski sensors. That barrier is beginning to fall as standard bodies have developed digital and low power secondary specifications. At present there are meters and relays that accept low power inputs, in some cases at cost savings. Digital input devices have been in field trials and will soon be available for general market use. (See Power Systems Engineering Research Center {PSERC} projects and for example K. P. Brand, et. al., [1].)

J. N. Blake is with NxtPhase T&D, Inc., Phoenix, AZ 85027 USA (e-mail: jblake@nxtphase.com).

A. H. Rose is with NxtPhase T&D, Inc., Phoenix, AZ 85027 USA (e-mail: arose@nxtphase.com).

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The benefits of digital signal processing have been discussed in many earlier publications, [2]. One system-wide benefit is that digital signal processing under the IEC 61850-9-2 format would allow for two-way communication and networking between equipment, which will facilitate better electrical grid control. Also, the interface barrier will be reversed between conventional and innovative optical devices. The cost of an optical sensor decreases with the digital format and the cost of the conventional increases.

Figure 1 shows the outputs that can be produced by any sensor and the standards that specify a particular output. If an optical sensor's principal output is typically digital, then that output would be in the lowest-cost and highest-quality data format.

The low-energy analog (LEA) output is the next output that is natural for an optical sensor to produce. Low-power operational amplifiers typically produce this output. However, as will be discussed in this paper, the conversion of the digital data through a digital-to-analog converter and then through an amplifier, degrades the data and places limits on

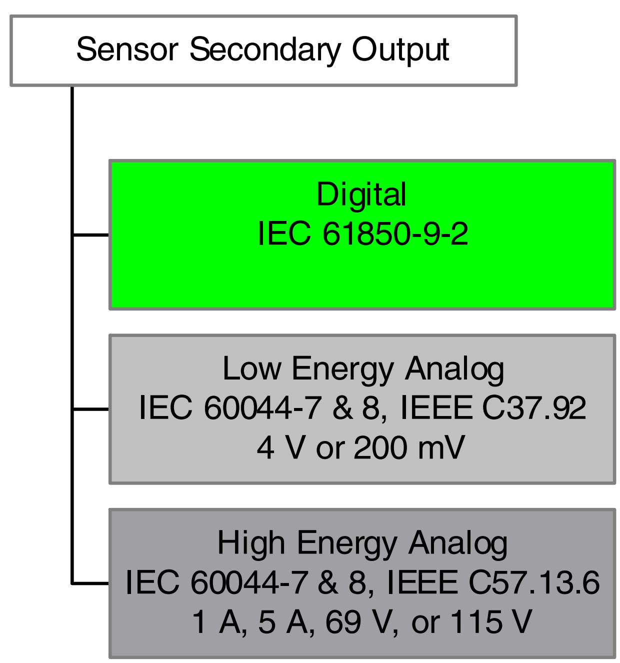

Figure 1. The output categories that a sensor can have according to IEC and IEEE standards.

both the low and high end of the dynamic range.

High-energy analog (HEA) outputs in an optical sensor are designed to emulate the conventional high power output, but because amplifiers have limited power, the outputs cannot drive electro-mechanical devices and only interface with low-burden (microprocessor-based) secondary equipment.

The overall accuracy of the power measurement with these outputs is dependent on the accuracy of not only the relay or power meter but also on the optical voltage and current transducers. While a great deal of standards and industry work is devoted to improving these individual components' linearity and accuracy, in reality the specific transducer-relay/meter combination determine the true measurement quality.

In this paper we will discuss the work on the secondary outputs presented by NxtPhase T&D optical products and the merits and uses of each type (digital, LEA, and HEA).

II. NxtPhase T&D Optical Current and Voltage Sensors

The NXCT uses the in-line Sagnac design described in detail in J. Blake, et. al., [3], [4]. These interferometric Sagnac sensors are stabilized with a phase modulator. The phase modulator allows the sensor to heterodyne the signal away from low frequency noise during the signal processing. The modulator also allows the interrogation of the sensor response function, which contains information about the health of the optical path and the impact of the optical path on the sensor scale factor. By looking at large portions of the optical response function rather than a single value, we determine if the sensor is still within specified accuracy limits. The basic output of the sensor is a digital word that can be sent directly to digital equipment or converted into a LEA output (200 mV or 4 V) or a HEA output (1 A or 5 A). The interferometric NXCT has exceptional stability, obtained using methods similar to those found in fiber gyros, [5].

The NXVT uses the Pockels effect in Bismuth Germanate electric field sensors distributed in a gas-filled column to measure the voltage between the line and ground. The design of this sensor is described in detail in F. Rahmatian, et. al., [3], [6]. The distributed field sensors with resistive shielding are virtually immune to pollution perturbation to the electric field. The output of the sensor is a digital word that can be sent to digital equipment, converted into a LEA output (4 V) or a HEA output (69 V or 115 V).

III. The Digital Optical Sensor Output

The system architecture of the digital signals is shown in Figure 2. The digital data flows from sensors to a merging unit (MU). The MU reformats the signals into a digital packet that can then be sent to a meter, relay, recorder, or any other

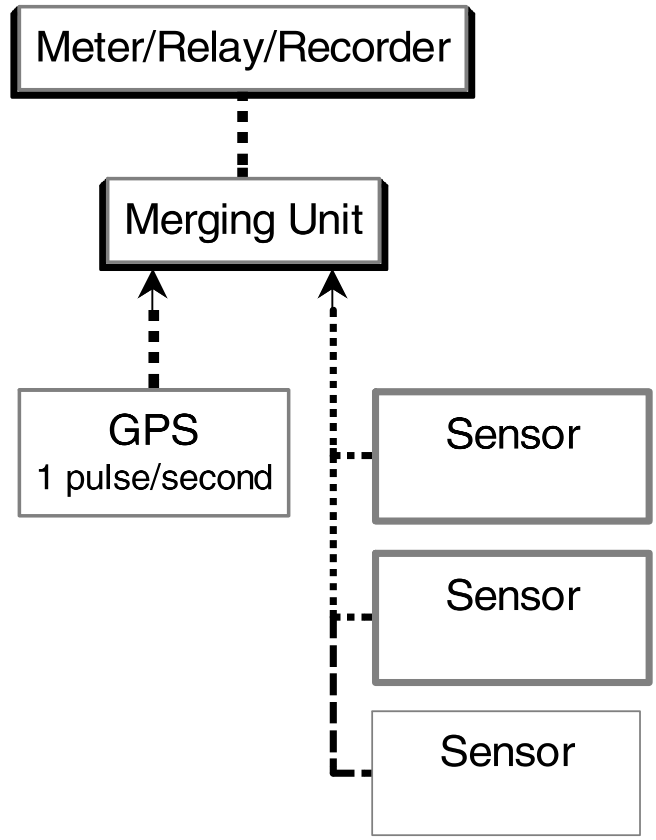

Figure 2. The digital architecture according to IEC 60044-8 and IEC 61850-9-2 is shown above.

intelligent electronic device (IED). The digital output of our sensor is presented by the MU in the format prescribed in the standard IEC 61850-9-2. The data stream to the MU is bi-directional allowing a network of sensors and secondary equipment to be monitored remotely.

The data from a sensor whose output is primarily digital offers the best information from that device. As will be shown in later sections of this paper, the digital-to-analog (D/A) conversion and amplification degrades or limits the linearity and dynamic range of the output, as well as adding cost to these measurement solutions. Sensors that are only analog, lose performance and add cost because of analog-to-digital conversion (A/D).

We have developed a MU and applied the data from our current sensor to the MU to demonstrate the performance gains acquired with a straight digital data transmission. The performance of our current sensor with digital output is such that it can be used as a secondary standard and will be evaluated for that purpose by NIST, [7]. Our current sensor can measure both AC and DC; thus it could be used as a transfer standard. The AC/DC linearity obtained is shown in Figure 3. The accuracy of the tests is within the accuracy of the test instrumentation (50 ppm for DC measurements and 500 ppm for AC measurements). The AC accuracy was limited by the comparison analog equipment. (We used an Arbiter 931A Dynamic Signal Analyzer, which has an

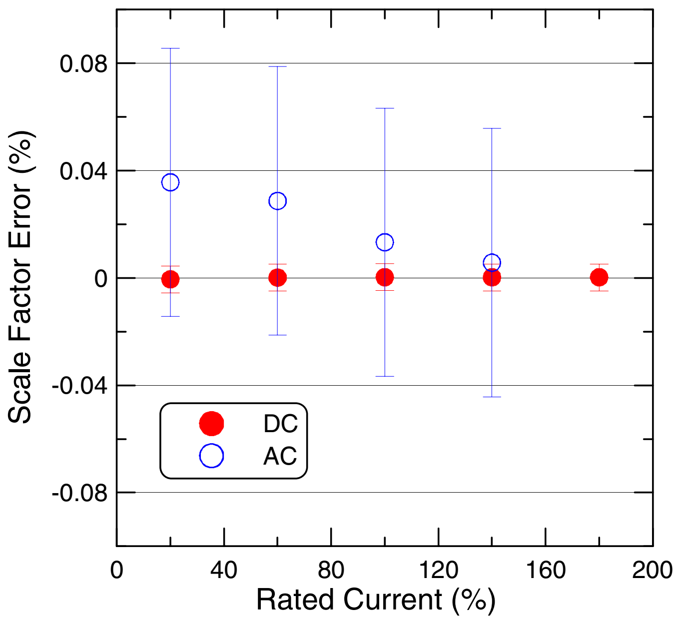

Figure 3. A comparison of the AC and DC measurement capability of a digital NXCT is shown.

uncertainty of 500 ppm). We believe the digital current sensor has sufficient accuracy to be used as a high current AC/DC transfer standard for power frequencies. The sensor can be calibrated using a DC current, and then used as a power frequency AC calibration reference with an accuracy equal to that of the DC calibration method. The sensor's 3 dB bandwidth is 2 kHz.

Similar results can be obtained with the voltage sensor digital output. A digital meter, relay or recorder could then use this data for improved revenue accounting, response time, diagnostics, or record keeping during events. In the future the functions of these devices could merge, but probably because of practice and network security the revenue and protection functions will remain separate.

IV. Low Energy Analog Optical Sensor Output

In the IEC 60044-7, 60044-8, and the IEEE C37.92, there are provisions for a low energy analog (LEA) output from an electronic transducer. The output is nominally 4 V for metering applications and 200 mV for CT protection applications. We specify a 5 kΩ burden. We use both of these outputs in our current and voltage sensors, to connect to various IEDs or to drive high-energy amplifiers. (The high-energy outputs will be discussed in the next section.) The main limitations of this type of output, as compared to a digital, are the degradation of the digital data through the D/A conversion and the voltage amplifier upper voltage limit; 11.2 V in this case. Even so, this output provides an inexpensive way for a digital sensor to interface with analog secondary equipment. At this time, only a select number of relays and recorders accept this output; no known power meters are available.

A/D and D/A converters are not perfectly linear devices.

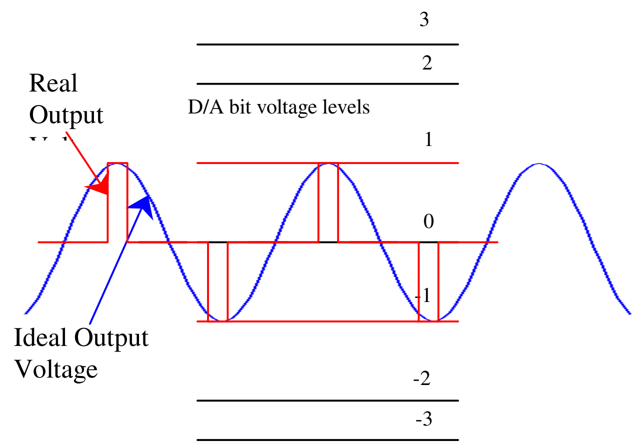

Figure 4. Non-uniform gain and loss of data for a small signal is shown.

They have non-linear bit spacing and a finite number of bits, which limit the maximum and minimum voltage output. The maximum limit is reached when the digital word exceeds the largest voltage the converter can reproduce. The minimum value error is subtle. The loss of measured power in a D/A is illustrated in Figure 4. As the sensor's signal falls between the least significant bits (1 and -1) of the converter, no output is presented to the analog amplifiers, resulting in large accuracy errors. At low levels the nonlinear bit spacing also affects the accuracy of the signal magnitude.

This problem also exists for secondary IEDs because of the, reciprocal, A/D conversion occurring there. The microprocessor-based secondary equipment converts the incoming signal, either voltage or current, into a digital word via an A/D converter. At low levels the signal is small enough that the non-linearity of the bits and the least significant bits again limit the accuracy, [8].

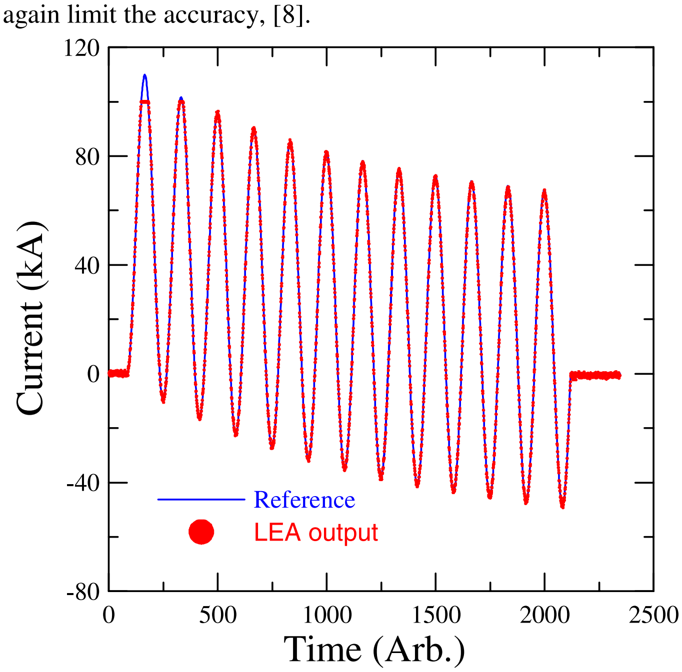

Figure 5. LEA output comparison of a >108 kA peak fully-offset-fault current, (60 Hz frequency).

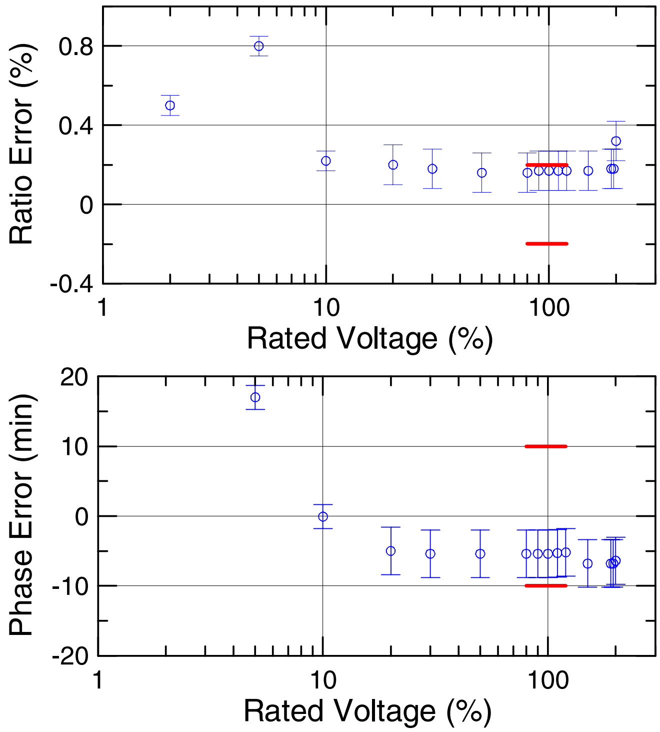

Figure 6. The ratio and phase error of an NXVT LEA output measured at the NRC-Canada. The bars in each graph are the IEC 0.2 accuracy class specification.

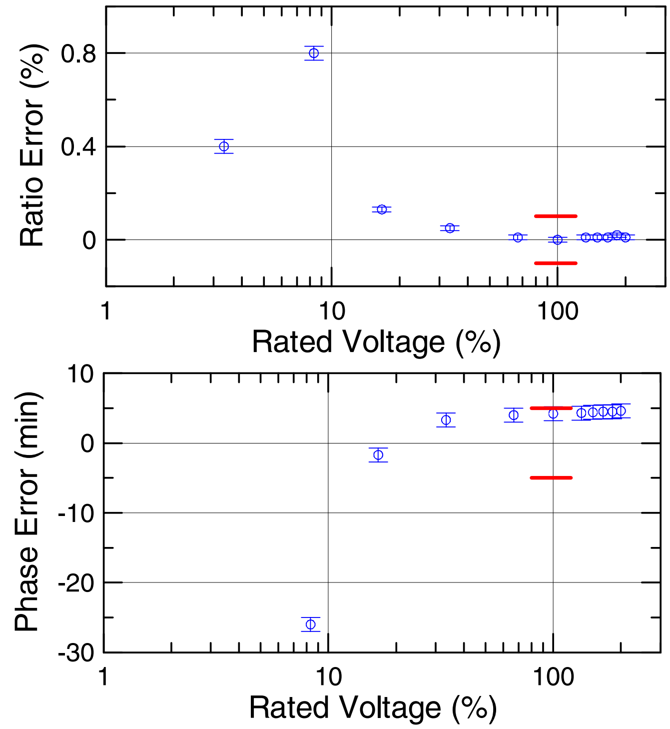

Figure 7. The ratio and phase error for a NXVT HEA output measured at the NRC-Canada. The bars represent the IEC 0.1 accuracy class specification.

Figure 5 shows a fully offset fault current peaking just above 108 kA. In this example, the National Instrument data acquisition system input amplifier saturates above 10.8 V, illustrating one of the problems with the analog signals. With the proper scaling of the LEA output, the NXCT and NXVT sensors can be IEC 5TPE protection class devices.

The LEA output of the NXVT has a wide dynamic range, primarily because the optical sensor and amplifiers all have wide dynamic range. A 345 kV class optical voltage sensor was evaluated at NRC-Canada from 5 % to 200 % of rated, [8]. The linearity of the sensor was such that with correct scaling it could be well within the IEC 0.1 accuracy class. The variation of the ratio from 80% to 190% of rated was about 100 ppm and in phase about 2 min. Figure 6 shows the ratio and phase linearity of the NXVT over the test range.

V. High Energy Analog Optical Sensor Output

The HEA output from an optical sensor is designed to emulate the conventional high power output of either 1 A, 5 A, 69 V, or 115 V at rated values. However, the HEA output from an optical sensor should not be confused with the high power conventional output. Amplifiers with limited power, drive the HEA output, thus the burden that these HEA amplifiers can handle is small, typically 2.5 VA or less. The HEA output is designed to fit into legacy applications with microprocessor relays and meters that have small burdens. Even with these limitations the HEA output is still desired until secondary equipment with LEA or digital inputs become universally available.

For metering current measurements, there are class 2 meters available to accept a 1 A HEA output from the NXCT. The 1 A metering HEA is less demanding on the amplifier than the 5 A protection HEA output. In an earlier paper, we have shown the improved performance of the NXCT 1 A HEA output for wide dynamic range metering, applicable to independent power producers and wind farm power production, [9]. We showed a range from 0.1 % to 150 % of rated current where the metering accuracy is held. The primary reason that lower currents cannot be metered with accuracy is the inherent conversion of the 1 A current into a digital word in the power meter. With an all-digital conversion lower ranges could be reached.

For metering voltage measurements a 69 V or 115 V HEA output is available from the NXVT. We had an NXVT-345 evaluated at the NRC-Canada and the HEA results are presented in Figure 7. The linearity of the NXVT exceeds the IEC 0.1 accuracy class. The variation of the ratio from 80% to 190% was about 100 ppm and in phase about 0.4 min.

For CT protection applications we have developed a 5 A HEA output. The amplifier is capable of producing 100 A_{rms} secondary fault currents for 100 ms and could also be used for 1 A secondary protection applications. Figure 8 shows the response of the amplifier for an offset fault current. The input to the amplifier is filtered for DC currents, because the output transformer on the amplifier saturates with large DC currents. The figure shows the offset fault for an IEC TPE class output,

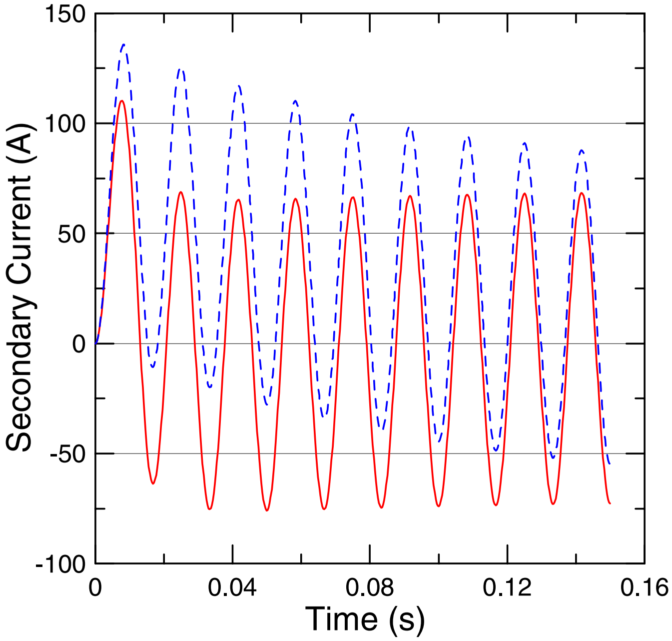

Figure 8. The HEA secondary current from 5 A protection amplifier showing the DC filtered (solid) [IEC TPZ] class and non-filtered output (dashed) [IEC TPE class].

dashed line, and the DC filtered output, which meets the IEC TPZ protection class.

VI. Conclusion

In this paper, we have shown that optical sensors with a digital output have accuracies that far exceed the limits of utility standards. Also, we have shown that the integrity of the measurement is reduced and the measurement cost is increased with increasing power amplification. We have shown that the NXCT and NXVT can have accuracies so great that they can be used as secondary transfer standards. Also, we report on a 5 A interface to facilitate the use of optical CTs with legacy microprocessor relays. With this secondary output, NxtPhase T&D now provides all the types of secondary outputs that standards specify. We have compared the digital, low-energy analog, and high-energy analog outputs for linearity and accuracy. This work has shown that direct processing of the optical sensor's digital outputs will alleviate problems of digital-to-analog and analog-to-digital conversion (non-linearity, amplifier voltage, and current limitations). Optical CTs and VTs have digital output capabilities and are ideally suited to all digital power metering and protection applications.

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VIII. Biographies

James Blake received his B.S.E.E. from U.C. Berkeley in 1981, and his Ph.D. in Electrical Engineering from Stanford University in 1988. He worked as a microwave antenna engineer at Ford Aerospace in Palo Alto, CA from 1981 to 1984. From 1988 to 1991 he was a Research Scientist at Honeywell in Phoenix, AZ working on fiber optic gyroscopes. From 1991 to 1999 Dr. Blake was a Professor of Electrical Engineering at Texas A&M University in College Station, TX. His research at Texas A&M concentrated on fiber optic gyros, flow sensors and current sensors. Since 1999, Dr. Blake has been Director of Research and Development at NxtPhase in Phoenix, AZ where he has concentrated on commercializing fiber optic current sensors for high-voltage applications. Also, Dr. Blake formed Precision Lightwave Instruments in 1998 to work on fiber-optic current standards. Dr. Blake has received an R&D 100 award for the development of the optical fiber current and voltage sensor in 2002.

A. H. Rose received the B.S. degree in physics at Abilene Christian University, Abilene, TX, in 1981 and the M.S. and Ph.D. degrees in physics at the University of Arkansas, Fayetteville, in 1983 and 1986. In 1986 he joined the U.S. Army's Ballistic Research Laboratory, Aberdeen Proving Ground, MD, as an NRC Postdoctoral Fellow. In 1987 he joined NIST, in Boulder, CO, to work on the development of optical fiber sensors, related optical measurements and standards. In 2001 he joined NxtPhase in Phoenix, AZ to work on optical fiber current and voltage sensors and the calibration of those sensor systems. In 2004, Dr. Rose began managing the production of the optical current sensor for NxtPhase T&D.

Dr. Rose has received an R&D 100 award for the development of the optical fiber current sensor in 1991, and the NIST Bronze Medal for the development of a standard retarder in 1998. He is one of the associate editors for Photonics Technology Letters and has served on the program committee for the International Conference on Optical Fiber Sensors. Dr. Rose is a member of the IEEE LEOS (since 2002), Optical Society of America (since 1987), and Sigma Xi, The Scientific Research Society (since 1986).