Interfacing Optical Current Sensors in a Substation

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Abstract: Optical current sensors are achieving increased acceptance and use in high voltage substations due to their superior accuracy, bandwidth, dynamic range and inherent isolation. Once deemed specialized devices intended for novel applications, optical sensors have risen to a performance level exceeding conventional magnetic devices.

Optical current sensors have pushed the limits of measurement beyond what is presently available with conventional technology. In order for users of optical transducers to realize the complete benefits available from this new technology, an understanding of the differences between conventional transformers and optical sensors is critical. Key users who must understand these differences include planners, apparatus engineers, substation designers, maintenance personnel, and system operators. Interfacing optical sensors to existing meters and relays is one of these key differences and will be the primary focus of this paper. Providing a simple method of interconnecting old and new technology is a necessary and required step in the path to acceptance of optical sensors, and if given this, it will ease the transition to advanced systems within a substation.

Keywords: Current measurement, current transformers, digital communication, optical fiber transducers, optical transducers, transducers, substation measurements, substations

I INTRODUCTION

The various components required to build the digital substation of the future are now available for utilities to purchase. These components lead to improved measurement, control, and protection of the substation with the expectation that lower costs and increased revenue will be achieved with the additional information, which is more accurate and accessible by the various users. Utilities have come to realize that knowledge on a real time basis enables improved decisions, and hence leads to real economic benefits.

With any new technology there is always enthusiasm and excitement about how the new development will revolutionize older technology, and most people will embrace the fundamental concept of the new technology. However, once the fanfare has died down, budgets are determined, resources assigned, and staff trained, there remains the headaches associated with integrating new technology. How will the designer interface the new technology with the existing infrastructure, without upgrading all components, and complete this task in a realistic timeframe? Demonstrating to utilities a fully working installation that meshes new and old goes a long way in convincing skeptics that the technology works, and that it will not complicate their jobs.

When the practical problem of integrating existing technology with advanced equipment, which has digital outputs and communications capability, is taken on, most designers will begin to pull out their hair and grunt to themselves, and their colleagues, in the hallways of the workplace. It is not a trivial task to accomplish. New must blend with old as seamlessly as possible. With this goal in mind, electronic outputs representing the measured value, which vary from digital to high energy 1A output signals, provide a solution that does not require a wholesale changeout of the old technology. Given a variety of available interfaces, the benefits of new technology can be combined with existing substation equipment and the user sees a clear migration path for future upgrades.

II INTERFACE OPTIONS

Interfacing optical current sensors with conventional meters and relays requires a fresh approach to bring signals into these devices. In conventional CTs, outputs are either 1A or 5A nominal for both metering and protection applications. These high energy output levels, while commonplace and easy to achieve from “iron core” CTs, are difficult and expensive to replicate using electronics based on an inherently digital signal.

While generally agreed that digital signals from measuring devices will dominate future substations, the short-term solution requires interfacing the devices with an existing analog substation infrastructure. How can a user who wishes to benefit from the use of optical sensing technology best implement these devices without resorting to a specific manufacturers complete product line, or without purchase of a “turn key” substation? Additionally, what communication protocol should be used? When international organizations have difficulty in establishing agreed upon standards, utility engineers in turn face

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difficulty implementing the digital substation. A complete digital substation will inevitably be available in the future, but how will it come about? The majority of the pieces are available today, but the difficulty lies in interfacing with older incompatible technology. Standards are still evolving. Manufacturers of meters and relays require time to evolve to fully digital inputs, and most importantly, people have differing opinions about the optimal path to a complete digital solution. Substation designers want an immediate solution that will be flexible enough to mate with existing equipment, yet be capable of evolving for the future.

One approach is a staged evolution. The transition to a complete digital substation can evolve by providing several simple methods to integrate old with new. New technology will find acceptance if users are given interface options that are easy to implement, similar to existing technology, which still provide the additional benefits of an advanced technology. When digital interface protocols are finalized and accepted by all parties involved, optical sensors will be in a position to provide these digital signals as an ideal technical interface. Interface options presently available to a user of an optical sensor include digital, low energy analog, and high energy analog outputs. This range of interfaces gives users flexibility in their designs.

A: Digital Output

The digital output from an optical current sensor, representing the primary current flowing, is available in a format consistent with IEC draft standard 60044-8. This draft standard specifies the digital signal that will emerge from a "merging unit" (MU), shown in Figure 1. The MU's function is to gather information from up to seven current transducers (3 measuring CTs, 3 protective CTs, and one neutral CT), and up to five voltage transducers (3 measuring/protective VTs, one busbar VT, and one neutral VT) whose signal is either of a digital format or an analog voltage output.

It is recognized that digital standards pertaining to substation communications for relaying, control, and data acquisition are evolving with many in various stages of becoming standards, such as IEC 60044-8, IEC 61850, and IEEE P1525. To further complicate the goal of using digital communications within substations, standards may be issued, but they must still gain acceptance with a large portion of the vendors and within the utility community.

Utilizing the digital signal for either metering or relaying gives the user the most accurate signal available, as compared to the low and high energy analog signals, at a lower cost. By not converting the digital signal to the analog domain, and possibly amplifying this signal, results in the greatest accuracy and dynamic range performance from the sensor with a lower overall cost.

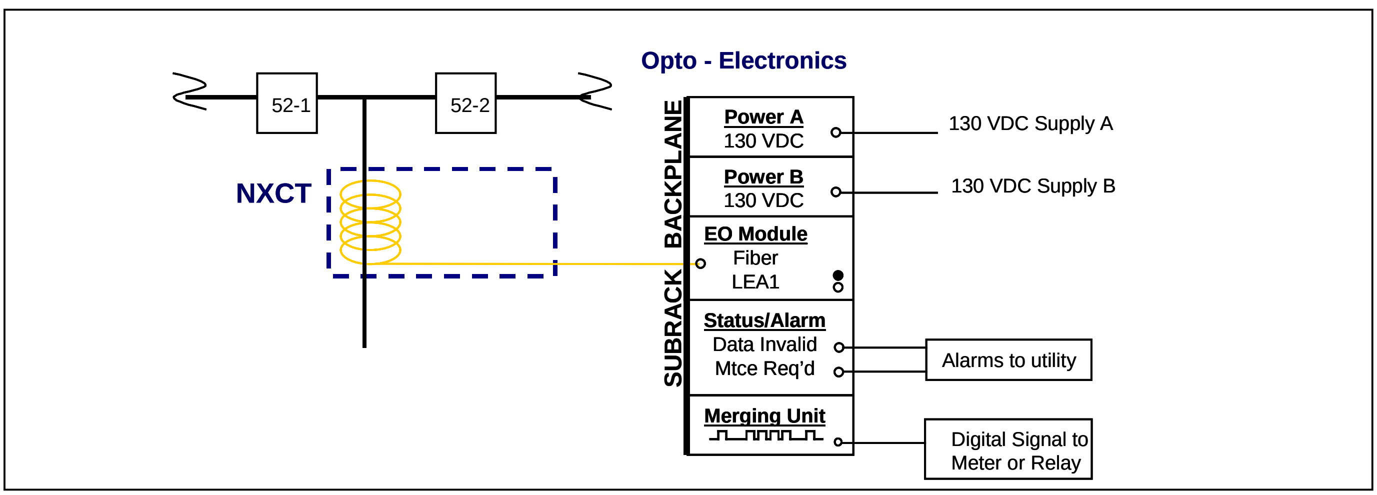


Fig. 1 Optical current sensor with digital output to digital meter or relay.

B: Low Energy Analog (LEA) Output

A low energy analog output from the electronics is selectable with several ranges depending on the user's requirements. For metering applications, the analog signal representing the primary current can be $2V_{RMS}$ or $4V_{RMS}$ nominal. The choice will depend on the meter interface available to the user. When using the signal for relaying, current would be represented by a 200 mV_{RMS} signal capable of 11.3 $V_{peak.}$ The 11.3 V_{peak} signal gives a maximum instantaneous value consistent with the worst-case fault condition that is 40 times the primary current. Figure 2 details a low energy analog (LEA) solution for either metering or relaying.

The LEA option while applicable for both metering and relaying, is ideally suited for protection applications. Relays are commercially available today to accept LEA signals from an optical CT. The LEA output, while not as accurate as the digital output signal, remains as an interim step until fully digital meters and relays are made available to users. Reduction in accuracy when compared with the digital output signal, can be on the order of 0.1% over the full range of the optical sensor.

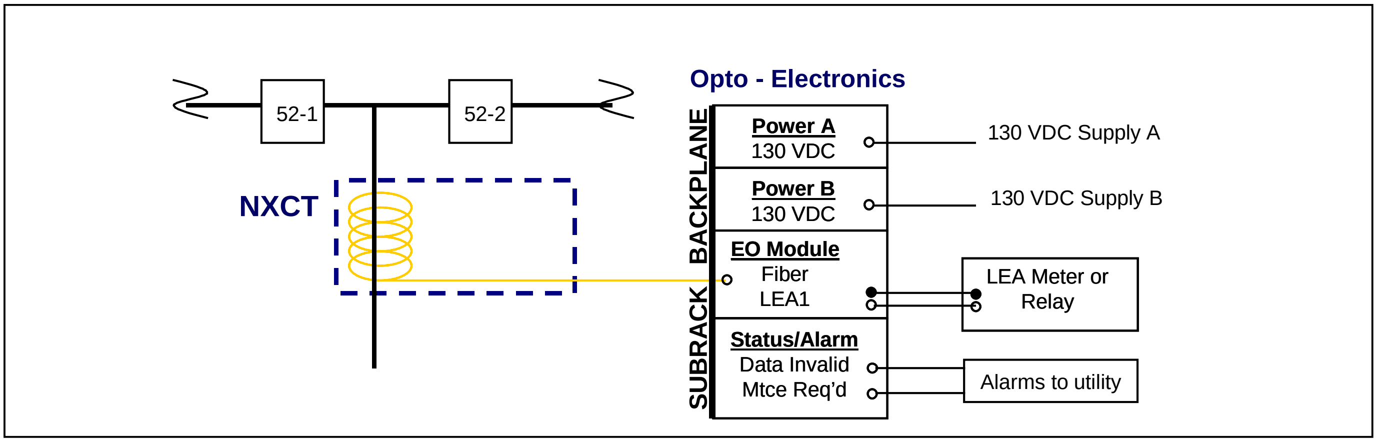


Fig. 2 Optical current sensor with low energy analog (LEA) output to analog meter or relay.

C: High Energy Analog Output

In order to mate new optical sensors with conventional meters, a digital signal from the opto-electronics is converted to an amplified 1A analog signal which can be fed into various manufacturers meters, as shown in Figure 3. The high energy analog signal is only compatible with meters since reproducing a 1A signal for relaying is both impractical and expensive. Similarly, a 5A analog output signal is not available for either metering or relaying for the same reasons. The 1A analog output can be utilized by several types of meters, and in the interim before a digital solution is available, will allow use of optical sensors within substations. A power amplifier that is fully compliant with all EMC, transient, and surge requirements allows it to be paralleled with a conventional CT. With this capability, an optical sensor can sum signals at a node. In Figure 4 an analog amplified signal is integrated with a conventional CT.

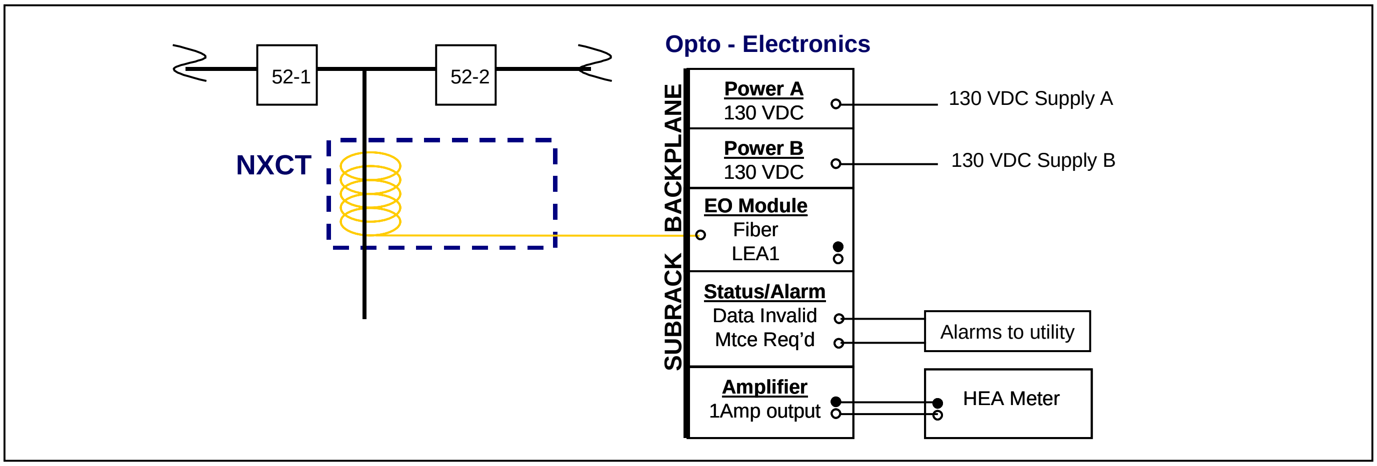


Fig. 3 Optical current sensor with high energy analog (HEA) output to analog meter.

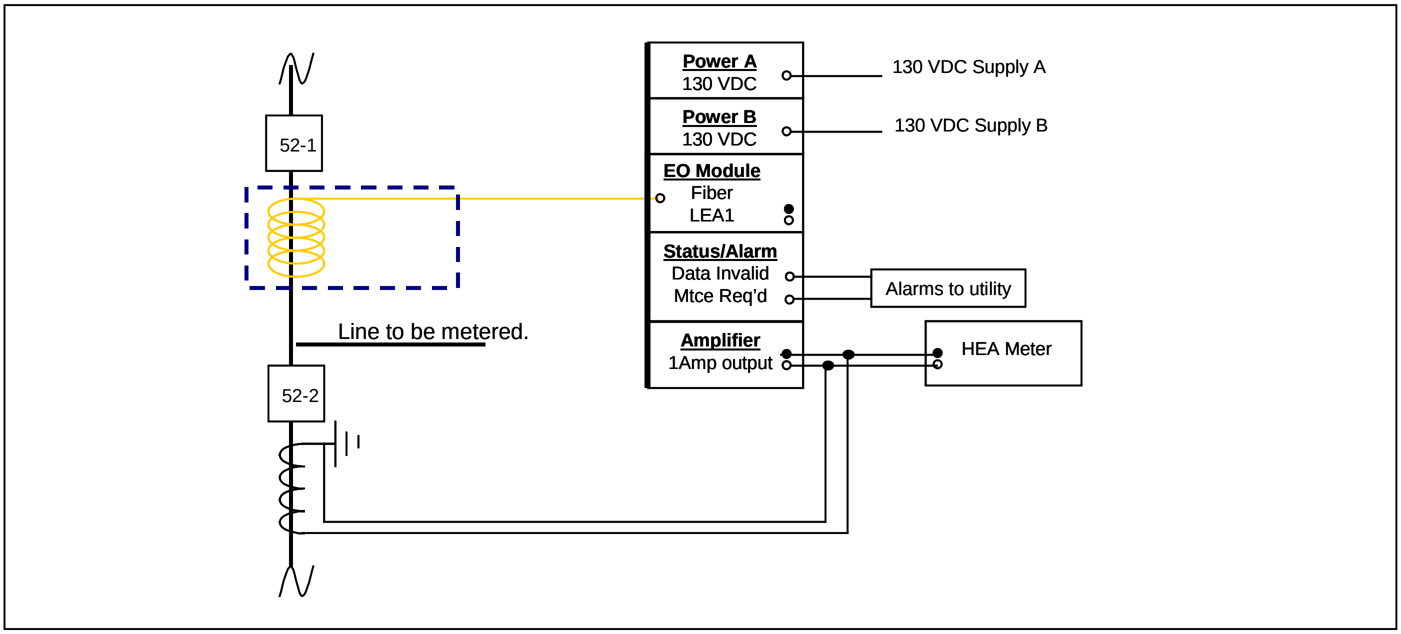


Fig. 4 High energy analog (HEA) output summed with conventional CT

III SELECTION OF AN OPTICAL CURRENT SENSOR FOR METERING

Optical sensors are inherently different from conventional iron core transformers. They measure the primary current based on optical sensing and create a digital representation of the current. This signal may be converted back into an analog signal and possibly amplified. When utilizing optical sensors, users must be aware of the implications of the various available sensor designs, as they may see peculiar results from their meters, especially at low primary currents.

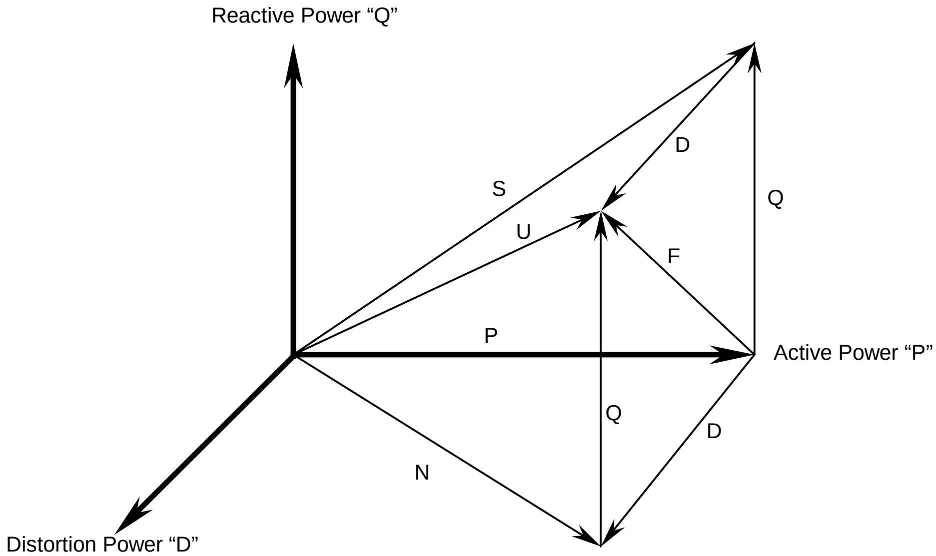
The observed peculiarities, and their dependence to the design of the optical sensor, are due first to the amount of noise contained within the output signal, and secondly to the method of calculating certain parameters within a manufacturer's meter. The first can be controlled by sensor manufacturers, the second can vary from meter to meter and therefore has limited ability to be modified. To achieve a successful metering system design, suitable for all available meters, the noise from the sensor must be reduced. Noise contribution, or alternatively, sensitivity of an optical current sensor, is important because meters may report incorrect results, such as high VARs, incorrect power factor, or high harmonic distortion. These incorrect readings will appear at low current levels, but depending on the design of the sensor, low may mean 100A or more flowing on the primary. By designing a sensitive sensor, as described in sections 4 and 5, the noise dependence can be reduced to a level below 5A primary, where it becomes insignificant.

In order to understand the implications of sensor design to metering, a more thorough description of metering and metering terminology is required.

Metering systems have become a critical component in the deregulation of the power system as generation, transmission, distribution, and operations are being separated into independent companies. With this break up of the utilities, an increasing number of metering points are being added, as power is no longer flowing within the same company. The power is crossing boundaries and money is exchanging hands. Metering has become more important and people associated with buying and selling power want to measure it with increased accuracy, at more places, and in the most cost effective manner possible.

Metering personnel generally may want to know how much power is flowing into and out of their system and at what power factor? A simple question that should be easy to answer, but will bring up more questions if it is to be properly answered. Do you want real or reactive power flow? This question is easy to answer and well understood, but what if someone wants to know what the phasor power is, or how much of the apparent power is due to distortion, or fictitious power? Distortion and fictitious power are not commonly understood, but become relevant terms when measuring signals with high harmonic content, or noise. These metering terms can be found in IEEE Standard 100-1996[1], "The IEEE Standard Dictionary of Electrical and Electronics Terms". This standard explains several terms not traditionally used when discussing metering, but they are essential if currents with high harmonic content are being metered or if noise is significant in a sensor.

The flow of power in any circuit is composed of real, reactive, and distortion power vectors, all of which form the "vector power (U)", in a circuit. Figure 5 illustrates the "power vector" components, followed by a brief description of the various components. (Note: For an in depth description of each definition, consult with the IEEE standard.)



Legend
P – active, or real power
Q – reactive power
S – phasor power
U – power vector, or apparent power
D – distortion power
F – fictitious power

Fig. 5 IEEE Std. 100 definition of the "Power Vector" U

Some metering books define the various metering parameters, similar to the IEEE definitions above, but in less detail. However, many do not specifically refer to "distortion power", or "phasor power", and most power terms are defined for "sinusoidal quantities" only. This simplification ignores the vector component that noise and harmonics introduce to power calculations. In the omission of these details, it confuses the reality of the situation by its lack of definitions, which do not give the required "language" to properly explain the power vector (U), as defined in IEEE Standard 100.

For example, power within a meter can be given on a per phase basis and a total polyphase power reading. Not always given by meter manufacturers, though, is a concise definition of what these display values actually are. For some meters, the per phase power is the apparent power per phase, and the total power is the phasor power; but they are all referred to as "power". Similarly, power factor can also be given on a per phase and total basis, both referred to as "power factor", but the per phase power factor is actually arithmetic power factor, and the total is phasor power factor. Tables 1 and 2 summarize both power and power factor definitions as defined in IEEE Standard 100.

The lack of concise information regarding power and power factor calculations may be typical to many meters, however, with an increasing emphasis on understanding harmonics, knowing which vector component of power is displayed by a meter becomes critical to all users.

Name	Symbol	Definition
Active (Real) Power	P	The active power at any instant in time t_0 is defined as the time average of the instantaneous power over one period of the fundamental wave, or: $$P = \frac{1}{T} \cdot \int_{t_0-\frac{T}{2}}^{t_0+\frac{T}{2}} p\,dt$$ where: p = instantaneous power T = fundamental period
Apparent Power	U	Apparent power is the magnitude of the vector power. $$U = \sqrt{P^2 + Q^2 + D^2}$$ where: P = active power Q = reactive power D = distortion power
Arithmetic Apparent Power	$U_{arithmetic}$	The scalar addition of apparent power for all phases.
Distortion Power	D	$$D = \sqrt{U^2 - P^2 - Q^2}$$ where: U = apparent power P = active or real power Q = reactive power
Fictitious Power	F	$$F = \sqrt{Q^2 + D^2}$$ where: Q = reactive power D = distortion power
Instantaneous Power	p	The instantaneous voltage multiplied by the instantaneous current. $$\begin{aligned} p = {} & E_1 \cdot I_1 \left(\cos\left(\alpha_1 - \beta_1\right) + \cos\left(2 \cdot \omega \cdot t + \alpha_1 + \beta_1\right)\right) \\ & + E_2 \cdot I_1 \cdot \left(\cos\left(\omega \cdot t + \alpha_2 - \beta_1\right) + \cos\left(3 \cdot \omega \cdot t + \alpha_2 + \beta_1\right)\right) \\ & + E_1 \cdot I_2 \cdot \left(\cos\left(\omega \cdot t - \alpha_1 + \beta_2\right) + \cos\left(3 \cdot \omega \cdot t + \alpha_1 + \beta_2\right)\right) \\ & + E_2 \cdot I_2 \left(\cos\left(\alpha_2 - \beta_2\right) + \cos\left(4 \cdot \omega \cdot t + \alpha_2 + \beta_2\right)\right) \\ & + \ldots\ldots \end{aligned}$$ shown as a double summation it becomes $$p = \sum_{r=1}^{\infty} \sum_{q=1}^{\infty} E_r \cdot I_q \cdot \left[\left(\cos(r-q) \cdot \omega \cdot t + \alpha_r - \beta_q\right) + \left(\cos(r+q) \cdot \omega \cdot t + \alpha_r - \beta_q\right)\right]$$ where: r = order of voltage harmonic q = order of current harmonic E = rms amplitude of harmonic voltage I = rms amplitude of harmonic current α = phase angle of voltage β = phase angle of current This multiplication results in a power that has a constant (ie DC, or RMS power) component and a time varying component. Over time, the varying component averages to zero.

Phasor Power	S	$S = \sqrt{P^2 + Q^2}$ where: P = active or real power Q = reactive power Note: This term was once referred to as “vector power”.
Reactive Power	Q	Reactive power is found similar to active power, but with the current waveform shifted by -90 degrees to obtain the quadrature component to the active power, which is the reactive power. Note: Some meters incorrectly report fictitious power as reactive power since they calculate reactive power by using the apparent power and the real power. This calculation is only true when the distortion power is very small compared with the other power components.
Vector Power	U	Vector power is essentially the same as apparent power, except that it is a vector, and hence has direction in relation to the other power definitions.

Table 1. Power Definitions

Apparent pf	$pf_{apparent} = \frac{P}{U}$ where: P = active or real power U = apparent power
Arithmetic pf	$pf_{arithmetic} = \frac{P}{U_{arithmetic}}$ where: P = active or real power U = arithmetic apparent power
Phasor pf	$pf_{phasor} = \frac{P}{S}$ where: P = active or real power S = phasor power

Table 2. Power factor definitions

IV OPTICAL CURRENT SENSORS FOR METERING

In order to reduce signal noise in an optical current sensor, one successful method is to wrap multiple turns of fiber around the conductor, thereby increasing the sensitivity of the device and “pushing” the noise level down to a level where it is insignificant. By increasing the fiber turns, the resulting signals replicated by the opto-electronics will provide meters with a signal that has superior signal-to-noise ratio (SNR), and therefore, will be able to be used with any meter, not just a customized meter matched to the characteristics of the sensor. Most utilities having one or possibly two meter manufacturer’s that they use on a regular basis, and these meters are accepted by all users, installers, and integrators of the meters. To inform them that their meter, which they have invested time and money into becoming familiar with and trained in its operation, is incompatible with a particular signal is simply not an option. Reducing the noise component on an optical current sensor allows usage with any meter manufacturer’s product.

Figure 6 illustrates the magnitude of the noise component in a single turn and a 16 turn sensor. The single fiber turn sensor, similar in noise sensitivity to a bulk crystal design, will have significant noise throughout the current sensing range, which can cause a meter reading RMS current to read higher current than is actually flowing on the primary line. VAR measurement may also read higher than actual depending on the calculation method. A sensor with several fiber turns pushes the noise to a level far below that of the single turn sensor. The implications of a sensor with increased sensitivity are that a user can use any meter commonly available and it will work with the optical sensor. When a sensor with high noise content is interfaced with available meters, readings will begin to get progressively worse as the current in the primary drops, and hence the SNR of the output signal decreases. Therefore, unless the meter examines pure 60 Hz signals, the meter may register incorrect values. Using multiple fiber turns, in conjunction with advanced optics and electronics, can overcome this limitation.

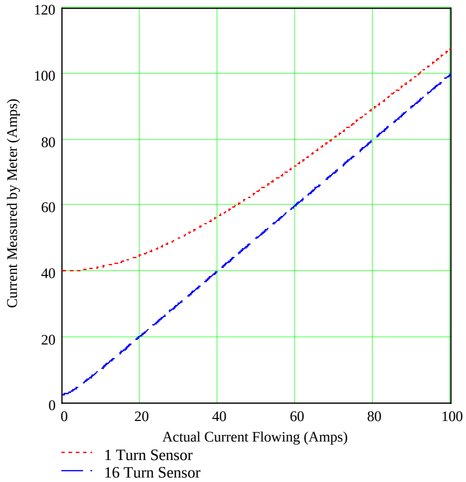
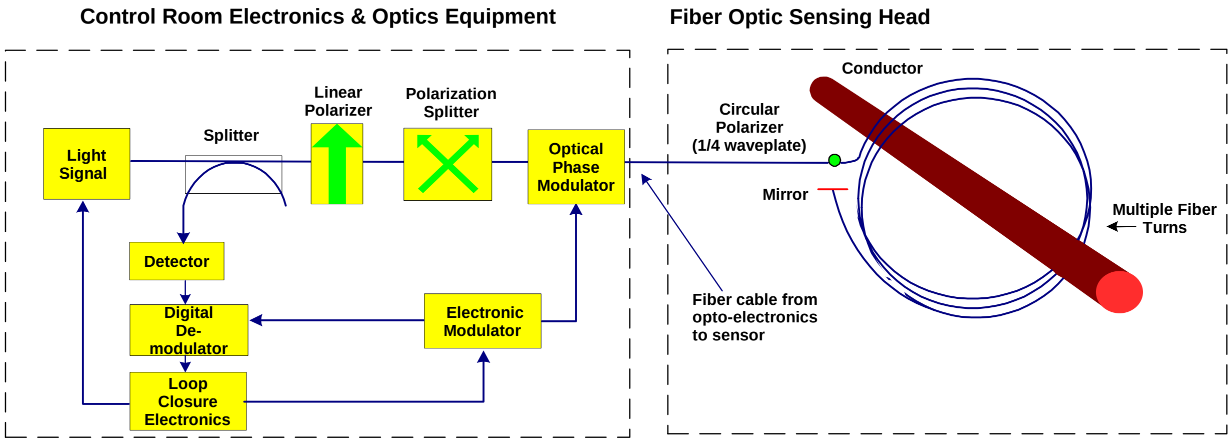


Figure 6 Current measured by "true RMS" meter plotted against actual RMS current.

V. FIBER OPTIC CURRENT SENSOR TECHNOLOGY

The fiber optic current sensor is the core of an optical current transducer. As shown in Figures 7 and 8, it consists of a light source, photo detector, optics and electronics coupled to a fiber sensor head wound around a current carrying conductor. The optical phase modulator is the "heart" of the current sensor and it, along with the electronics and optics, can provide a highly accurate measurement of current.



1. A light source sends light through a waveguide to a linear polarizer, then to a polarization splitter (creating two linearly polarized light waves), and finally to an optical phase modulator.
2. This light is then sent from the control room to the sensor head by an optical fiber.
3. The light passes through a quarter waveplate creating right and left hand circularly polarized light from the two linearly polarized light waves.
4. The two light waves traverse the fiber sensing loop around the conductor, reflect off a mirror at the end of the fiber loop, and return along the same path.
5. While encircling the conductor, the magnetic field induced by the current flowing in the conductor creates a differential optical phase shift between the two light waves due to the Faraday effect.
6. The two optical waves travel back through the optical circuit and are finally routed to the optical detector where the electronics de-modulate the light waves to determine the phase shift.
7. The phase shift between the two light waves is proportional to current and an analog or digital signal representing the current is provided by the electronics to the end user.

Figure 7: NxtPhase NXCT Fiber Optic Current Sensor Optical Block Diagram

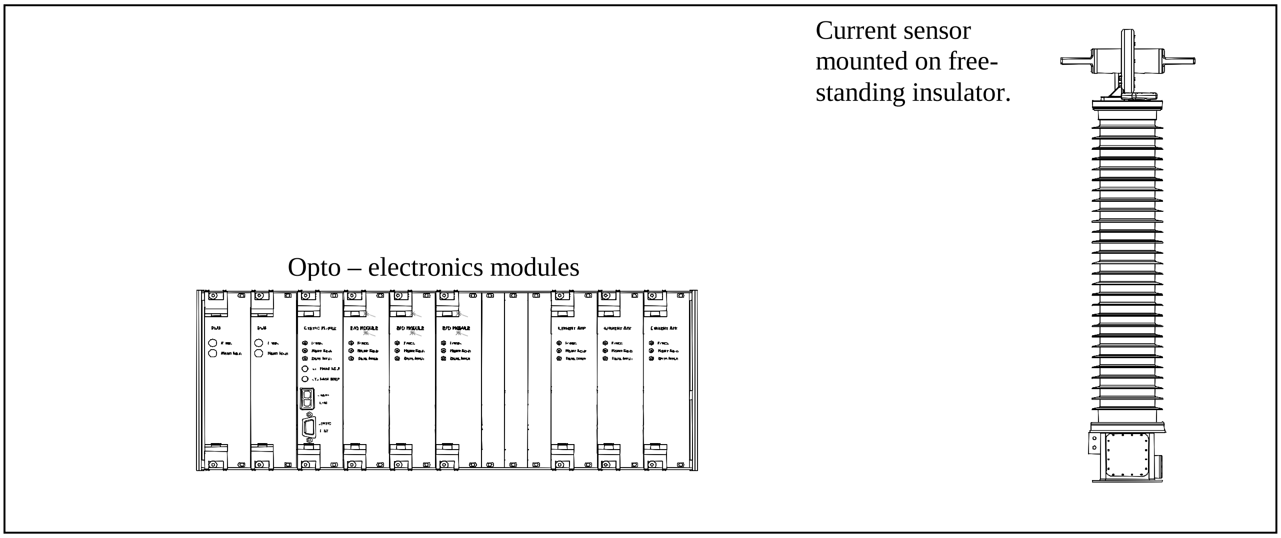


Figure 8 Fiber optic current sensor physical components (NTS)

VI CONCLUSION

Optical current sensors, in principal, perform the same function as conventional magnetic CTs; they measure current on the primary conductor and give an output signal that is representative of the primary current. The main difference to an optical sensor is that the signal is inherently digital in nature.

This digital signal, which is the best signal representing what is actually occurring on the primary conductor, has ability to be converted back into the analog world and amplified. This conversion and amplification of the signal, while highly illogical at first glance, permits optical sensors to be used immediately with available analog meters. When digital interfaces evolve and mature, the optical sensors with their inherent digital signals will be poised to offer further performance benefits with reduced cost, as the digital to analog conversion along with amplification can be eliminated.

Optical sensors are relatively new to the power industry and when interfacing them with existing meters or relays, a user must examine and understand the detailed characteristics of the sensor, since the design can significantly influence overall performance of a metering system.

VI REFERENCES

[1] IEEE Standard 100-1996, The IEEE Standard Dictionary of Electrical and Electronics Terms, Sixth Edition

BIOGRAPHIES

James Hrabliuk, an Applications Engineer with NxtPhase Corp, graduated from the University of Manitoba in 1989 with a Bachelor's Degree of Science in Electrical Engineering. After graduating, he worked at Manitoba Hydro for 11 years primarily as a Substation Design Engineer, and later as a Protection Design Engineer. James is a member of the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) and the IEEE.