Intelligent Measurement for Grid Management & Control

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Abstract

This paper describes the application of measurements derived from intensity modulated optical sensing technology, how they enable "network-centric" rather than "device-centric" monitoring of electrical phenomena and grid operations, and the distinguishing capabilities and advantages of this technology. The paper will discuss several applications for the technology that highlight how it can become a key enabler on the path to a more intelligent Grid.

Introduction

The Smart Grid *is* the future power grid – a consistently better performing, more resilient and more intelligent grid shaped by societal evolution and enabled through the application of 21st century digital technology. In all modern, digitally controlled networks, the quality of the underlying information used to drive the algorithms is the fundamental building block that enables effective, efficient network operations. Until now, this "information layer" for the power grid has been primitive by modern standards - fundamentally limited by the physics of conventional instrument transformer (CIT) sensing devices and low bandwidth, slow communications systems. The industry has continued to function, largely because the original concept of centrally generated power, radially distributed and locally monitored primarily for protective purposes still describes the overwhelming majority of power systems. Change, however, is accelerating, and the limitations of these systems are becoming increasingly apparent. Intermittent renewable resources, distributed generation, digital inverters, variable frequency drives and over-utilized transmission lines, are some of the innovations and trends that are exposing the limits of this legacy system and creating the need for an entirely new approach to control. The industry has responded with IEC 61850 and other design standards to allow for digital information processing, but as yet, it has not developed a solution to the underlying data problems. In short, the total vector error of the measurements must be reduced and more consistently repeatable over long periods of time than is possible with either conventional or non-conventional instrument transformers.

This paper focuses on this critical information layer. It begins with a review of the physical limitations of existing measurement devices and the problems which these cause when attempting to use unreliable data for advanced network control. The central part of the paper then introduces a new class of optical measurement devices, referred to as "Intensity Modulation", which solves both the problems of legacy ITs and the shortcomings of earlier optical techniques which caused them to fail in electric power applications. This new technique is adapted from military applications that have been deployed in extremely harsh operating conditions for decades and is showing extreme promise as the solution to next generation information for the electric power industry. The paper concludes with a discussion of how these devices could be deployed in the existing grid, and the dramatic impact which this 21st century information layer could have on realizing the potential of a truly intelligent grid.

The measuring platform of the Grid today and its problems

A conventional instrument transformer (such as a current transformer; a potential (or voltage) transformer, which may be inductive or capacitive (CCVT); or a combined current and voltage instrument transformer) is "intended to reproduce in its secondary circuit, in a definite and known proportion, the current or voltage of its primary circuit with the phase relations and waveforms substantially preserved."[1] The electromagnetically induced current or voltage waveform(s) in the secondary circuit(s) of the instrument transformer (IT) should then be of an easily measurable value for the metering or protective devices that are connected as the load, or "burden", on the IT. Conventional instrument transformers are relied upon extensively to provide knowledge of system current or voltage at the locations where they are installed for these energy consumption awareness or protective purposes.

Unlike a power transformer which acts as an extremely efficient conduit in the power system, generally manipulating the current and voltage (sometimes phase) of energy as it flows through, instrument transformers use the ratio transformation characteristics of a transformer's operation to create "eyes" peering into the system for system visibility and control purposes. Conventional ITs have sufficed in this capacity for years, filling a relatively simply defined purpose, but there are some fundamental characteristics associated with the use of inductive transformation that inhibit how well and consistently these instrument transformers can "see" into the system, and now that the purpose is becoming more complex, they are becoming inadequate.

Central to this limitation, is the fact that when using an instrument transformer, the IT (i.e., the sensing device) becomes a part of the system (the measured) that is being observed. The measurement circuit is electrically coupled to the measured which by definition affects its ability to observe what is truly happening at that point on the system. In fact, the long applied industry strategies when selecting an IT are focused on how to minimize both the influence of the IT's presence in the circuit (because it is not desired to measure this) and the system's influence on the IT (which affects the ability of the IT to measure accurately). The upshot is that ITs have an operating window in which the odds of "getting it right" in terms of accuracy and repeatability is maximized. This is reflected by the pseudo-linear part of the IT's saturation curve, a.k.a., operating curve. The challenge is to navigate the variables that will bump the IT out of this 'window of accuracy' (moving the IT to a non-linear region of its saturation curve) while the irony is that there is no way to do this or to know whether the IT is operating "in" the window or "out" without taking an outage to remove the IT from service for test and verification.

Many variables impact the accuracy of instrument transformers, including:

1. *Current/voltage level* – The dynamic range of a conventional IT is determined from its saturation curve. To achieve its rated accuracy, the conventional instrument transformer must operate in the quasi linear region of this curve and typically achieves approximately 20 dB of dynamic range at a constant fundamental frequency (e.g. 60 Hz)[2]. When system conditions result in current or voltage magnitudes that exceed this range, an IT's accuracy deteriorates and may be pushed into saturation, particularly in the case of a metering IT which generally has a lower saturation threshold than a protection IT. This, in turn, hinders the IT's subsequent capability to resume accurate scaled reproduction of currents or voltages that then fall back within its 'guaranteed' range.
2. *Frequency variation* – Instrument transformers are 'tuned' for operation at line frequency (60 Hz in the U.S.). Changes in frequency alter the saturation curve of the IT and thus the accuracy of measurements at non-line frequencies cannot be guaranteed.
3. *Saturation* – Core saturation causes the IT to operate in a non-linear area of its saturation curve, which significantly deteriorates accuracy and can dramatically influence its functionality. There are several mechanisms that can cause an IT to saturate, all of which occur as a result of normal field operations:
    a. Burden variation – The burden is determined by the circuit connected to the secondary winding of the IT; as the ohmic burden increases, the IT core is more likely to saturate. In

[1] "C37.110-2007 IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes", IEEE, New York, NY April 7, 2008.
[2] J.D. Ramboz and O. Petersons, "NIST Measurement Services: A Calibration Service for Current Transformers", NIST Special Publication 250-36, U.S. Department of Commerce, Gaithersburg, MD, June 1991.

fact, the accuracy of an IT is only guaranteed if burden does not increase beyond a defined threshold. The burden may increase by adding or replacing (metering or protective) devices or with age due to corrosion, loose connections and broken stranded wires of the secondary electrical cabling connecting the IT to the device(s); so even if excess burden capacity was planned and existed at installation, over burdening is possible as the system ages. Temperature may also result in undesirable changes in burden.

b. Transient induced residual magnetism, or eminence – Residual magnetism can occur as a consequence of high fault currents containing transient components. Residual magnetism increases the flux density at which the (IT) core operates; therefore, the exciting current increases. Since much of the primary current is required for excitation, the secondary output is notably reduced and distorted on alternate half cycles, consequently, deteriorating the accuracy. Additionally, eminence effects in protective current transformers (CTs) are not predictable and hard to recognize during normal operation. Consequences include false operation of differential protection and failure to operate in real over-current situations as the CT's signal is distorted due to the residual magnetism in its core[3].
c. Geomagnetic-induced current (GIC) conditions – The presence of a quasi dc component in the primary winding of an IT results in a higher operating point on the excitation curve, and may affect steady-state and transient performance of the IT.[4]

A rather well-known IEEE survey which cataloged percentage remnant flux measured in 141 current transformers on a 230 kV system, revealed that 43% of this population were operating with over 40% residual magnetism.[4] Without regular outages for eminence verification and demagnetization when necessary, the accuracy and dynamic range of an IT can decline materially, which is bad enough news for its intended localized use. But on a compounded scale, i.e., a wide-area network of measuring nodes, it carries completely debilitating consequences. With unknown and varying accuracy at any given node, this results in unmanageable inconsistency between measurements, even under steady-state system conditions. The situation deteriorates further during system disturbances that can produce significant voltage and current swings at frequencies varying quite notably from 60 Hz, such that, conceivably, the system state deduced by information from these strategically sited nodes could become completely irreconcilable.

In the advanced visibility and control systems that the industry is trying to create, this measurement instability creates a number of problems that are just now starting to be understood. For example, pharos measurement units (PMUs), which rely on input from conventional ITs, are difficult to synchronize due to a combination of random measurement error in the measurements and poor clock design, thus resulting in unacceptable levels of total vector error. Distribution Fault Anticipation (DFA), a smart technology which relies on a database of fault signatures that must be built, doesn't work well because measurement instability impacts repeatability. Without repeatability, the same fault, at the same location will produce a varying 'signature' each time. Harmonic analyses are not possible because of an IT's frequency dependence and, for the same reason, it is nearly impossible to monitor and analyze sub-synchronous oscillations.

Intensity Modulated (IM) Optical Sensing Technology

Intensity modulated optical sensing technology solves the information infrastructure problem that will increasingly limit the development of the smart grid.

[3] P. Fong, "Testing Current Transformers with the Modeling Concept", T&D World Magazine, June 7, 2011.
[4] "C37.110-2007 IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes", IEEE, New York, NY April 7, 2008.

The fundamental solution to accurate information is to find a physical solution that can observe the system without being electrically coupled to the system, or measured. This concept precludes any of the IT products either currently available or under development. Instead, it requires a completely new approach to measurement.

Starting in the late 90's, the electric power industry began to experiment with optical techniques that used interferometeric wave and phase modulation as the physical underpinnings of an electrically decoupled measurement system. Unfortunately, this equipment has generally failed in field applications due to its extreme sensitivity to temperature and EMI.

To solve this problem, a new approach based on recently declassified military applications has now been adapted to the needs of the electric power grid – thus achieving the objective of a highly accurate and reliable measurement device that is not electrically coupled to the measured.

How the technology works:

The U.S. Naval Research Lab (NRL) has been a leader in optical sensing research for over 50 years. Similar to the power industry's experience with interferometric sensors[5], the Navy found that the acute temperature and EMI sensitivity of these devices caused them to fail in mission critical, field applications. To solve these problems, the NRL ultimately developed a highly stable, *intensity* modulated optical sensor that has no temperature sensitivity, no susceptibility to EMI, no frequency modulation, and has been proven to operate accurately in very harsh conditions for long periods of time. This technology, vetted over decades, has now been adapted to measure voltage, current, phase and other characteristics of electric phenomena, and can deliver accurate, stable and reliable performance in rigorous field applications on the power system.

An intensity modulated optical monitoring system consists of a transducer that is located within the force field it is measuring, a light source located some distance away, a fiber optic transmitting cable, at least one fiber collector or return cable, and power electronics.

A sensing element is held securely within the transducer; this is a material that is deliberately selected based upon the measuring application and which responds to changes in the force to which it is subjected. This force is characterized by a magnitude and frequency. In the case of acoustic measurements, and as shown in Figure 1, this material is a diaphragm. Physical displacement of the sensor is being directly measured but this movement is ultimately a function of the force (i.e., the measured) acting upon it.

Light of a known intensity (P_T) from a light-emitting diode (LED) is coupled into an optical fiber for transmission to the sensing element where it is modulated in accordance with the state of the measured. Reflected light of a varying intensity (P_R) is collected by at least one return fiber for transmission back to a photo-detector.

[5] As gauged by general polled feedback

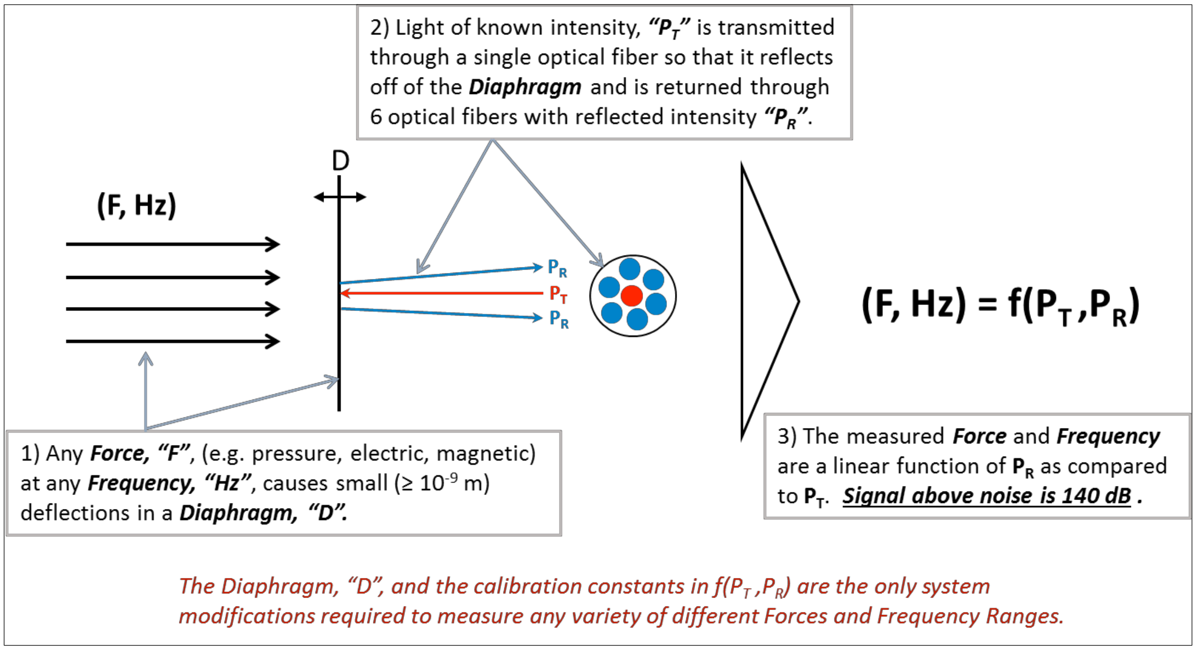

Figure 1
Intensity Modulated Optical Sensing – Fundamental Concept

The intensity of the light returned through the fiber correlates to the force exerted on the sensing element and the frequency with which it is changing. As an example, consider an acoustical measurement. As sound changes, the diaphragm moves and the resultant distance between the fiber probe and the diaphragm changes. Note that the fiber probe is stationary; it is the movement of the sensing element that alters the distance between the probe and the sensor. If that distance becomes smaller by way of displacement of the diaphragm towards the fiber probe, the reflectance changes and the intensity of the reflected light captured by the return fibers decreases (Figure 2). As the distance increases, more reflected light is captured by the return fibers and, consequently, P_R increases (Figure 3).

One transmit fiber and only one return fiber is depicted in Figures 2 and 3. The use of multiple return fibers amplifies the sensitivity of this intensity modulated technology, resulting in the ability to detect displacement changes of the sensing element on the order of 10^{-9} meters.

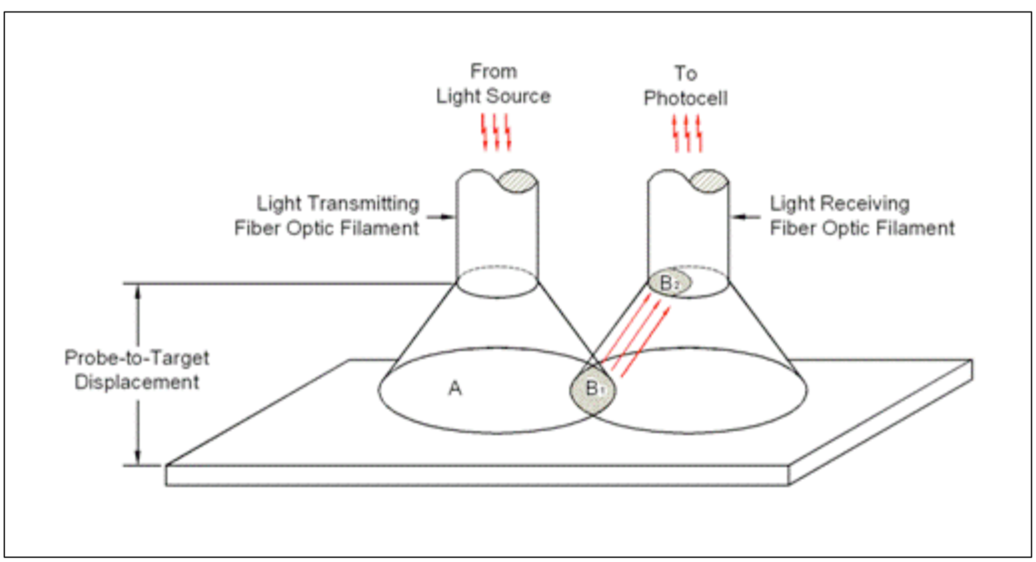

FIGURE 2[6]

P_R Decreases as Displacement between Probe and Diaphragm Decreases

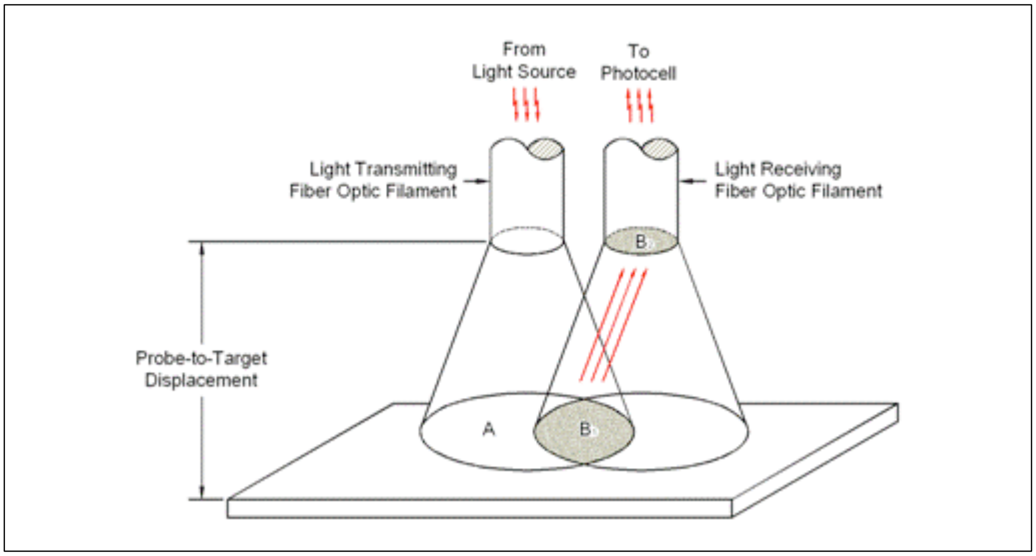

FIGURE 3[7]

P_R Increases as Displacement between Probe and Membrane Increases

Adapting Intensity Modulated Optical Sensors to Measure Electrical Phenomena:

Laws of physics are used to adapt the intensity modulated (IM) optical sensors to measure current and voltage. For example, principles of Lorentz's Force are applied to build the IM optical (AC) current sensor.

A Lorentz force, given by F = BLI and illustrated in Figure 4, will result when a current (I) carrying conductor passes through a non-varying magnetic field with flux density, B for some length, L.

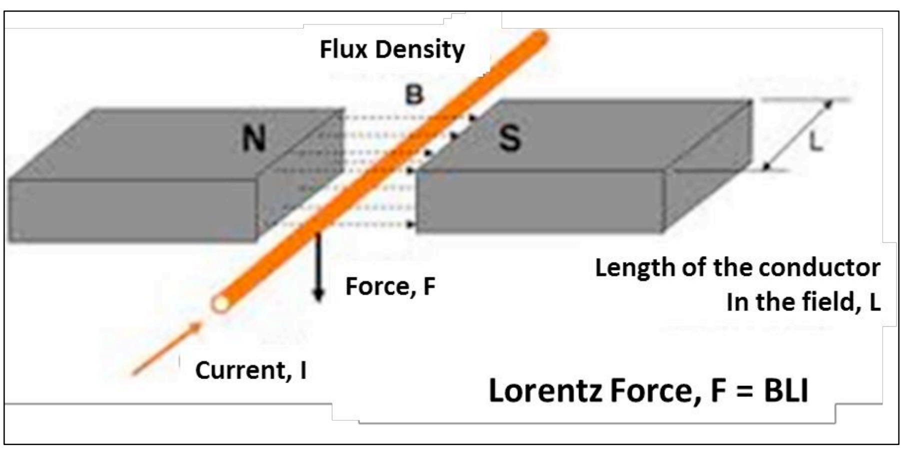

FIGURE 4

[6] Yury Pyekh, "Dynamic Terrain Following: NVCPD Scanning Technique Improvement", Fig. 3.7, Thesis Presented to the Academic Faculty of Georgia Institute of Technology, August 2010.
[7] Yury Pyekh, "Dynamic Terrain Following: NVCPD Scanning Technique Improvement", Fig. 3.8, Thesis Presented to the Academic Faculty of Georgia Institute of Technology, August 2010.

Lorentz Law

Accordingly, the current sensing element (Figure 5) connects to the line conductor; as current changes, variations in the Lorentz Force will result in the physical displacement of the sensing element. The intensity of light reflected back will therefore alter proportionally to the changes in the current.

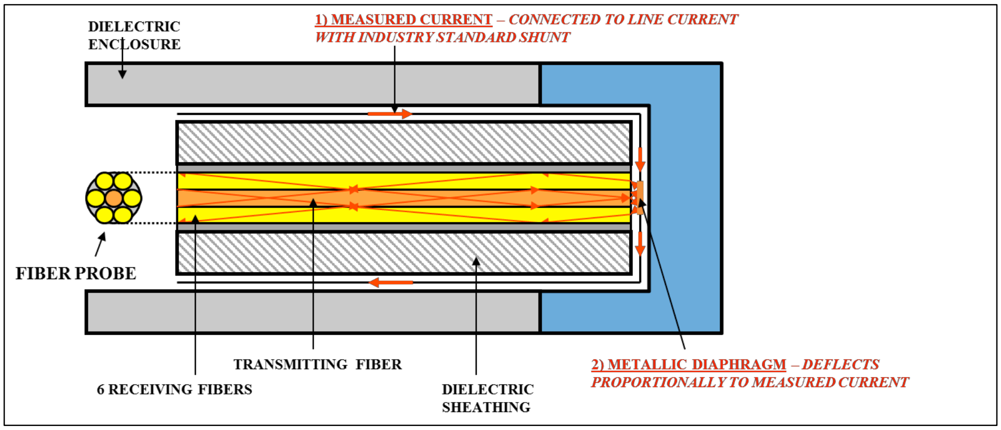

FIGURE 5
Intensity Modulated Fiber Optic Current Sensor

For voltage measurements, the selection of the sensing element is key. Here, a piezoelectric material is selected that has very stable physical characteristics that vary in a known way as the electric field in which the material is placed varies. A reflected surface affixed to the end of the sensing element will physically displace, therefore, as the material deflects relative to changes in the electric field.

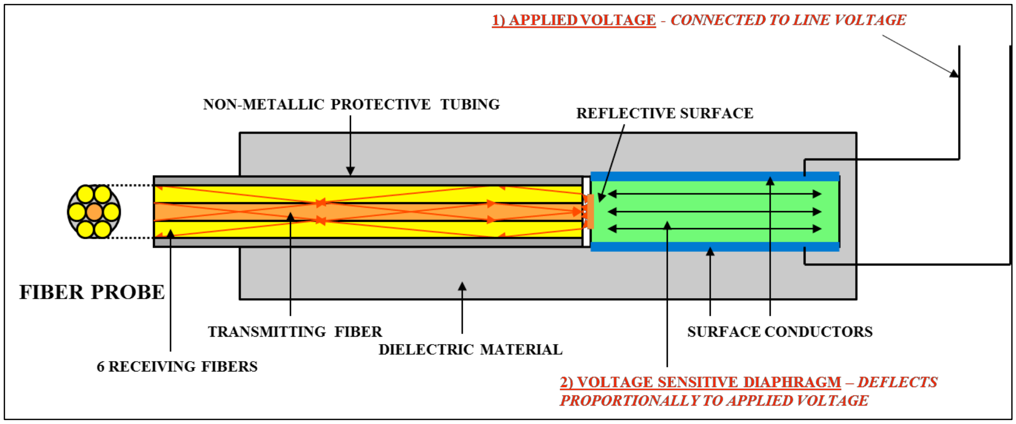

FIGURE 6
Intensity Modulated Fiber Optic Voltage Sensor

The IM optical current and voltage sensors are housed in a common transducer. The physical dimensions of these sensors are very small; length, its maximum dimension, is typically shorter than a few inches. This makes it possible to hold several sensors within one transducer, including IM optical temperature sensors.

Advantages

Accurate, Repeatable Measurement over an Extremely Wide Range of Values and Frequencies

The fact that Intensity Modulated (IM) optical sensing is passive, non-ferromagnetic and non-interferometry based is central to why this technology delivers a step-change improvement in performance over both conventional instrument transformers and interferometry-based optical equipment.

First, because of its passivity, an IM optical transducer does not disturb the (power) system it observes. The sensing element is non-conductive and the transducer is electrically decoupled from the grid; light is the 'exchange medium' of the transducer and an electrical system is not altered by light. The transducer therefore 'sees' exactly what exists on the power system and this creates notably higher accuracy than what can be achieved by even the most accurate of metering class instrument transformers.

Second, because IM optical sensing is not ferromagnetic and electrically de-coupled, traditional burdens have no influence on the transducer and the power system cannot negatively impact its measuring capability. IM optical sensors have no saturation curve; their equivalent operating "curve", and therefore performance, is perfectly linear throughout their wide measurement range. By removing variables introduced by system and burden influences, which have plagued the performance of conventional ITs in unpredictable ways for decades, the industry gains automatic assurances that the IM optical transducer is maintaining the accuracy it should at all times. This creates consistent accuracy and therefore, repeatability. Consistent and precise measurement is one of the principle requirements for enabling fully centralized network control capabilities, while repeatability, which only comes from being consistently accurate, is essential to any smart data-recognition based technology.

A third advantage of IM optical sensors non-ferromagnetic based operation is that frequency has no influence on its measuring capabilities. While varying the frequency does alter the shape of a saturation curve that defines the operating characteristics of a conventional IT, it has no effect on the linear operating curve of an IM optical sensor. IM sensors can measure voltage and current at frequencies from quasi-DC to several thousand Hertz. There are no concerns about resonant frequencies associated with inductive and capacitive voltage transformers. This measuring technology therefore affords the power industry the opportunity to view a broad range of non-fundamental frequency components with the same accuracy as measurements at the fundamental frequency (50/60 Hz) and therefore, to perform incredibly insightful power quality studies.

While the pseudo-linear range of a conventional IT's saturation curve is not large, affording only an approximate 20 dB dynamic range, the linear range of operation of an IM optical sensor delivers an approximate >130 dB dynamic range. This means that a single IM optical current sensor, for example, can measure an extremely large fault current, and at once, an exceptionally small harmonic current with identical accuracy. An IM optical system's measuring range is only limited by its noise floor, which is much lower than any other conventional or non-conventional field measurement device that is currently available.

Figure 7 gives a visual representation of the range of (current/voltage) magnitudes over which a conventional IT will yield accurate measurements (the vertical height of the blue shaded area at 60 HZ) and the limiting influence of frequency on a conventional IT's accurate measuring capabilities (as given by the diminishing height of the blue-shaded area as the frequency decreases/increases). In contrast, the much broader, frequency independent, and notably more accurate measuring capabilities of an IM monitoring system are indicated by the encompassing white backdrop that frames the graph in Figure 7.

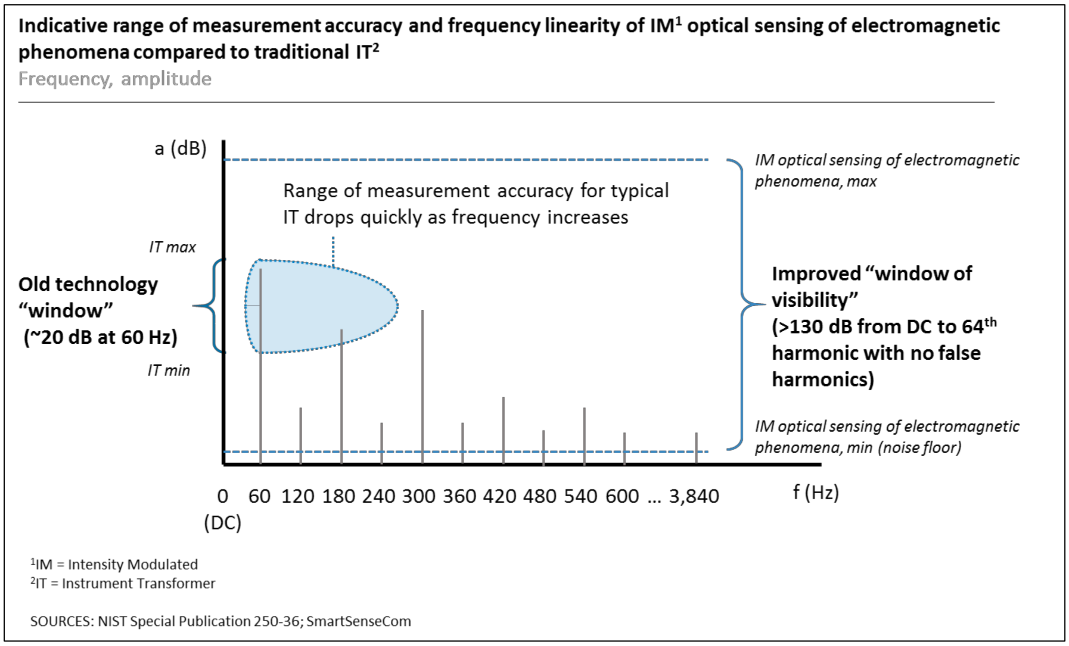

FIGURE 7
Accuracy/ Linearity as a Function of Frequency
(For an IM Optical Monitoring System versus a Conventional IT)

Safety and Risk Reduction

A separate, but equally important, advantage of passive IM optical sensors is safety and risk reduction in the unlikely event of the IM optical system's failure. With a conventional IT, the electrical grid extends all the way to the meter or protective device and the possibility exists for workers to be injured or even killed if they were to inadvertently come into contact with an open-circuited CT secondary. In contrast, the equivalent "secondary" side of an IM optical transducer is fiber optic cable carrying light. It presents no safety hazard. Moreover, should a conventional IT fail, it typically brings the circuit down with it, either due to catastrophic fire or a fault that trips the breaker. In comparison, the IM has no influence on the power system it is observing, and if it should fail, the power system would typically continue to operate as usual.

An additional benefit of being non-ferromagnetic is that periodic field testing to verify operating characteristics and insulation integrity is not necessary for an IM optical transducer. In fact, because an IM optical transducer is electrically decoupled from the grid, there is no requirement for the use of dielectric materials such as oil or SF6 in the device. The combination of these factors reduces O&M costs and expedites safe system restoration after outages.

Applications

IM optical monitoring systems solve the information infrastructure problem, strengthen the grid, and subsequently enable the applications that make the grid more intelligent. These applications, described more fully below, include "network-centric" monitoring of electrical phenomena and grid operations; increasing DLR capacity utilization; Volt/VAR and power flow monitoring; broadband power quality measurements; DC/ geomagnetic ally-induced current (GIC) monitoring; and fault locating on transmission lines, feeders, cables and devices. At the most fundamental level, IM optical monitoring systems are a safer, more reliable and more accurate replacement for conventional ITs, whether for metering or protection.

Smart grid applications such as wide-area measurement systems (WAMS) are now possible because of the ability of IM optical monitoring systems to deliver extremely accurate, consistent and stable measurements at all critical nodes in the power system, and provide this information in real-time through GPS and specialized clocking. Presently work is being done to implement synchronous wide-area transmission system monitoring for early warning systems using IM optical monitoring systems as a platform.

In another arena, IM optical monitoring systems are helping to achieve full value from Dynamic Line Rating (DLR) systems, which bring the industry one step closer towards maximizing grid efficiency and reliability by providing system operators with the knowledge, at any given time, of the maximum (and fluctuating) real-time capacity of transmission lines. Often, the DLR exceeds the static line rating, affording operators the increased latitude to keep economic dispatch of generation in place that otherwise would have to be prematurely shut down. However, to capitalize on this additional transmission capacity, the industry and its regulators must have the confidence to dispatch it. IM optical monitoring systems provide knowledge of the actual loads existing on the transmission system and what part of this load is reactive (VAR monitoring capabilities). Moreover, because IM optical monitoring systems can be mounted on a tower with no ground connection or micro-station required, this technology solves measuring challenges that arise at radial transmission taps (system nodes created outside substation boundaries), which usually exist in rather remote areas.

Power quality monitoring is another particularly intriguing application that is improved significantly through IM optical monitoring systems. The power industry has never before had access to the extremely accurate, highly granular data across an extensive range of frequencies that IM optical solutions deliver. Such capability will provide a new opportunity to manage harmonics and quality issues associated with renewables integration.

Information contained at non-fundamental frequencies has been explored and applied in “off-line” electrical testing for some time because of its diagnostic insights (e.g., variable frequency power factor testing, dielectric frequency response, and sweep frequency response analysis). From an “on-line” power system perspective, imagine what might be learned from and about variations in harmonic (and other non-fundamental frequency) rich signatures – what they convey about the condition of the power system. For example, a rise of a 2^{ND} harmonic current magnitude for a sustained period of time may indicate that a transformer has been pushed into half-cycle saturation; this often is indicative of the presence of DC current entering a transformer. Since an IM optical monitoring system has the capability to measure quasi-DC currents, such as GIC, these systems are also being installed on the neutrals of wye-connected transformer windings to identify or confirm such occurrences and, further, to precisely quantify the DC component present.

IM optical monitoring systems are able to measure DC voltages as well and are currently being deployed for use in high-voltage DC transmission line monitoring.

As discussed previously in the paper, accuracy and stability begets repeatability, which is critical in the development of fault locating technologies. These technologies fundamentally rely on a database of signatures that reflect power system responses to varying fault conditions. Such capability may be achieved on a transmission or distribution level, for overhead or underground cable alike but the success in identifying fault location pivots in part on how well these anticipated system responses were initially chronicled. IM optical monitoring systems provide the repeatability in measurement that will make such systems practical.

Conclusion

Before the power grid can become smarter, it must become stronger. This entails improvement in the grid’s infrastructure. A major infrastructure component is the information layer which is supported by sensing, measuring and monitoring devices. In order to enable many “smart-grid” technologies, these sensing and measuring devices must advance. For technologies that rely on accuracy at point of measurement as a critical component of their success, conventional instrument transformers cannot deliver because of their inherent characteristics associated with ferromagnetism. This paper has explored these characteristics and explained why they manifest as insurmountable "intelligence" problems.

An optical solution called Intensity Modulated (IM) optical measuring was introduced that resolves the grid's present-day measuring inadequacies and is different than earlier optical techniques which, while promising, have proven to be unstable under field conditions due to extreme temperature instability and electromagnetic interference. An IM optical system was described along with some example adaptations for its use in measuring electrical phenomena. Advantages of IM optical transducers, rooted in their passivity and non-ferromagnetic characteristics, were enumerated. These include a step-change improvement in accuracy; hardening to otherwise influencing 'environmental' variables resulting in stability and consistency in measurements, and therefore, repeatability; the ability to observe the power system more comprehensively than ever before through one transducer; and significant enhancement in personnel and system safety.

Finally, several applications presently being implemented with IM optical monitoring systems as the facilitating component were reviewed, highlighting how this technology can become a key enabler on the path to a more intelligent Grid.