OPTICAL CTs (MOCTs)

1845 - Faraday Effect in Optical Mat'ls
".... a rotation in the plane of polarization of linearly polarized light under the influence of a magnetic field parallel to the direction of light propagation."

$$\Theta_{ROT} = \mathbf{V} \int \vec{H} \cdot d\vec{\ell} \quad \text{radians}$$

where

$\mathbf{V}$ = Verdet Constant, $\frac{\text{rad}}{\text{A-turn}}$

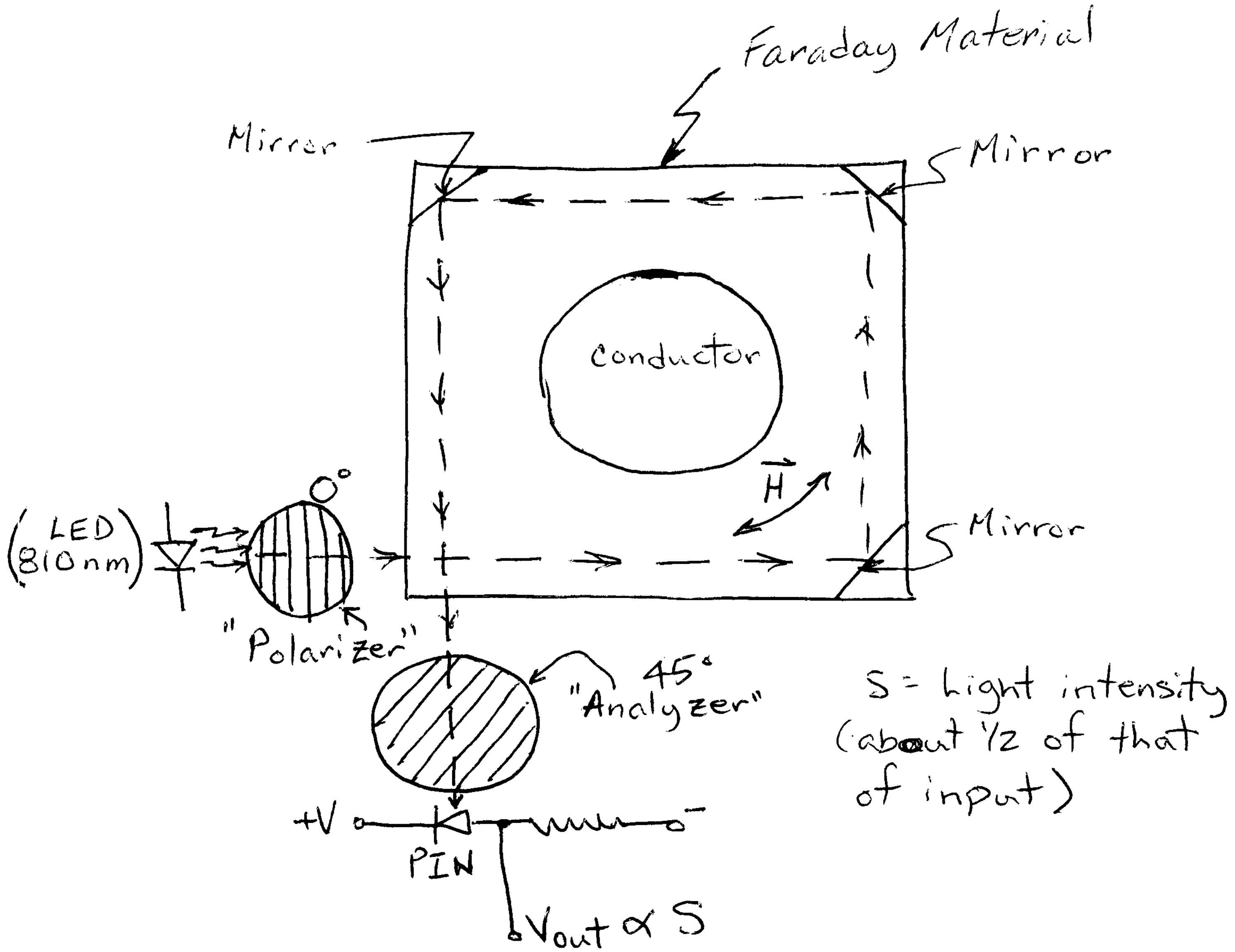
ℓ = integration path

$\mathbf{V}$ depends on wavelength of light.
@ $\lambda = 810$ nm, $2.5 \times 10^{-6} < \mathbf{V} < 20 \times 10^{-6}$ $\frac{\text{rad}}{\text{A-turn}}$

"Faraday Rotators" - materials that exhibit this behavior. For example,

Quartz	3.1×10^{-6} rad/A-turn
SF-57	16.1×10^{-6}
SF-6	13.9×10^{-6}
BK-7	2.7×10^{-6}

$\mathbf{V}$ also changes markedly for $T < -20°C$, decreasing about 5% at $-40°C$,



Since a closed path around the conductor is made, according to Ampere's Law:

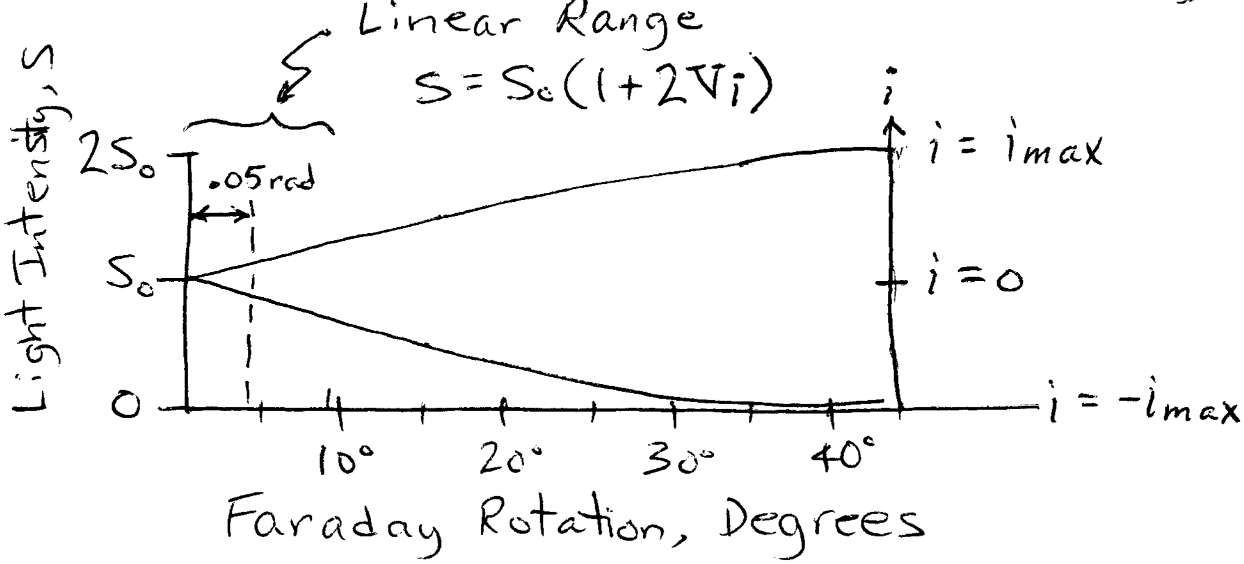
$$\Theta_{ROT} = V \oint \vec{H} \cdot d\vec{l} = Vi$$

The output light intensity S_0 occurs for $i = 0$ (no rotation). In general,

$$S = S_0 (1 + \sin 2\Theta_{ROT}) \cong S_0 (1 + 2\Theta_{ROT})$$

$$= S_0 (1 + 2Vi)$$

For small rotations, ($2\Theta_{ROT} < 0.1$ rad),



$S = S_0$ when $i = 0$, and increases or decreases depending on direction and magnitude of current flow. Since

$$\Theta_{ROT} = \mathcal{V} i$$

and

$$i = \frac{\Theta_{ROT}}{\mathcal{V}}$$

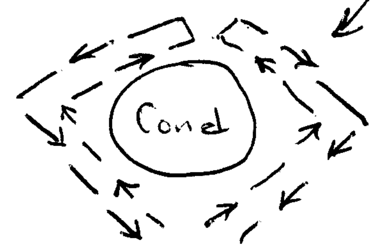
and

$$-45° < \Theta_{ROT} < +45° \Rightarrow i_{max} = \frac{\pi/4}{\mathcal{V}}$$

Material	$\mathcal{V}$	i_{max}	i_{max}, "linear"
SF-57	16.1×10^{-6}	48.8 KA	3105 A
SF-6	13.9×10^{-6}	56.5 KA	3597 A
BK-7	2.7×10^{-6}	291 KA	18,520 A

$|\Theta_{ROT}| \leq 0.05$ rad

- For measuring small currents, the MOCTs sensitivity may be increased by
  - Multiple loops of conductor
  - Choose material with larger V
  - Zig-zag light path
  - Multiple loops of light beam



- (Use small V and shortest optical path for large currents)

	345-KV MOCTs	Magnetic CTs
Bandwidth	1 – 10,000 Hz	40 - 2500 Hz
Saturation	No	Yes
Weight	350 lbs	9600 lbs
Accuracy	±0.2%, 20-40,000 A	±10%
Cost (1995)	$70K	$96K
Interface	Must Convert	0-5A S-S

18.6.5 Magneto-Optical Current Transducers

From: Greenwood ©1991

The magneto-optical method of measuring current depends for its operation on the Faraday effect in optical materials. This phenomenon, first reported by Faraday in 1845, manifests itself by a rotation of the plane of polarization of linearly polarized light under the influence of a magnetic field parallel to the direction of light propagation. The rotation is proportional to the integral of the H field along the integration path, i.e.,

$$\theta = V \int H\, dl \qquad (18.6.4)$$

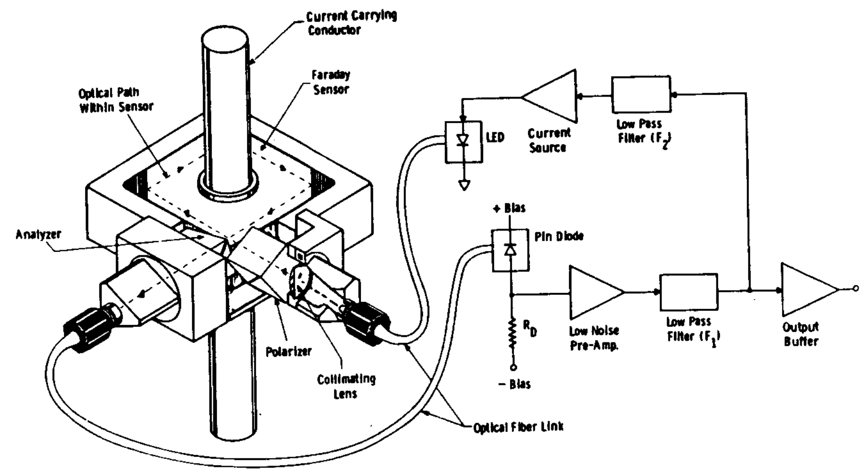


Fig. 18.26. Schematic of transducer head showing connections via multimode fibers to light source and detector components of electronic interface (Courtesy of Westinghouse Corp).

where l is the path length and V is a material constant known as the Verdet constant. The Faraday effect is most pronounced in materials known as Faraday rotators, which include quartz and other types of glass. The Verdet constant depends on the wavelength of the incident light; values in the range $0.25 \times 10^{-5} < V < 2.0 \times 10^{-5}$ rad/amp-turn for a wavelength of 810 nm are typical for different glasses. V is positive if the direction of rotation of polarization is the same as the direction of current flow in a solenoid around the light path which produces the magnetic field. The absolute direction of rotation is the same regardless of the direction of light propagation. Therefore, the total rotation can be increased by reflecting the light back and forth through the field.

A specific embodiment of magneto-optical current transducer, due to Westinghouse, is described in reference [9] and illustrated in Fig. 18.26. It will be seen that the optical path surrounds the conductor, so that Eq. 18.6.4 becomes

$$\theta = V \oint H\, dl \qquad (18.6.5)$$

By Ampere's law

$$\oint H\, dl = \text{the current enclosed } (i) \qquad (18.6.6)$$

therefore

$$\theta = Vi \qquad (18.6.7)$$

that is, the rotation is a function only of the current enclosed by the light path and is unaffected by nearby current-carrying conductors. If the current is looped through the optical path N times, $\theta = VNi$.

The complete MOCT system (Fig. 18.26) consists of the optical components, light source and detector, and an electrical interface which provides an output voltage proportional to the total current through the window of the MOCT. The optical components are the two optical fibers, two collimating lenses, a polarizer and analyzer, and the magneto-optical material. The light source is a LED and the detector is a PIN silicon diode. The electrical interface consists of amplifiers as shown.

The polarizer and the analyzer are oriented so that their polarizing axes are at an effective angle of 45° to one another. This is accomplished by rotating one with respect to the other or by the use of a half-wave plate oriented at an angle of 22.5° to the plane of the polarizer. Under these conditions the output intensity S at the analyzer for a rotation θ of the plane of polarization in the magneto-optical material is given by

$$S = S_0(1 + \sin 2\theta) \cong S_0(1 + 2\theta) = S_0(1 + 2VI) \qquad (18.6.8)$$

where S_0 is proportional to the light source intensity and dependent on the attenuation in the light guide's polarizer magneto-optical material, etc. The approximation $\sin 2\theta = 2\theta$ is valid within 0.2% for values of 2θ less than 0.1 rad and the replacement of 2θ by 2VI is exact for a properly constructed MOCT.

The optical fibers and collimating lenses are chosen so as to minimize optical losses in the system. This is accomplished by using as large a diameter optical fiber as can be effectively coupled to the LED (typically 300 μm), large diameter d (limiting aperture) of the combination of the collimator lens polarizer and analyzer, and magneto-optical material (typical 2.5 cm for a MOCT with a total path length of 50 cm), and by using as long a focal length collimating lens as permitted by the numerical aperture (NA) of the fiber, i.e. focal length $= d(2NA)$.

1995 APC

MAGNETO-OPTIC CURRENT TRANSDUCER OPTICAL METERING INSTALLATION AT GIBSON STATION SWITCHYARD

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ABSTRACT

This paper pertains to the application and installation of optical current sensors used for metering. The purpose of this paper is to discuss the theory of the magneto-optic current transducers and the details of the application of MOCT's in a revenue metering system at Gibson Station.

INTRODUCTION

The basis for the MOCT (magneto-optic current transducer) is the interaction between the magnetic field of the primary conductor and the optical activity of glass material. The relationship between the magnetic field and the amount of light transmitted through the optical transducer is directly proportional to the amount of current flowing in the primary conductor. This magneto-optic activity is known as the Faraday effect.

The failure of the metering current transformers on the 34509 line at Gibson Station Switchyard provided an ideal opportunity to apply the new MOCT technology. One advantage of the MOCT's is the elimination of catastrophic failures like that observed in oil filled torrial wound current transformers.

Optical systems have many advantages over conventional systems; however, it has a low energy output that will drive electronic meters, but will not generate the 5 amperes required by electro-mechanical devices.

Optical technology applications began in 1986 with a combined effort between TVA and ABB. The following list gives an indication of the growing interest in MOCT technology, for both metering and relaying.

YEAR	VOLTAGE CLASS	COMPANY	APPLICATION
1986	161KV	TVA	METERING
1989	138KV	HL&P	METERING
1989	161KV	TVA	METERING
1990	345KV	CON EDISON	METERING
1990	161KV	TVA	DISTANCE RELAY
1992	69KV	PG&E	METERING
1992	138KV	HL&P	DISTANCE RELAY
1992	23KV	DUKE POWER	METERING & RELAY
1992	26KV	PSE&G	RELAYING
1992	230KV	PSE&G	METERING
1992	500KV	TVA	RELAYING
1992	345KV	PSI ENERGY	METERING

Table 1

PRINCIPLE OF OPERATION

The Faraday effect is the basis for the operation of the MOCT. The diagram in Figure 1 on page 2 shows how the rotator material, the current carrying conductor, the magnetic field, the polarizer, the analyzer, and light, interact in a magneto-optic effect which enables light to be used to measure current flow in a high voltage conductor.

As Figure 1 also illustrates, the current flow in the conductor sets up a magnetic field. When the rotator material, which is optical glass, is subjected to a magnetic field, it will become optically active or conduct light. As the light rays are polarized into a light beam, which means that all the light rays are aligned in the same plane, the polarized light rays are then conducted through the optical rotator material. The phase orientation of the light beam is rotated as it transverses through the rotator material and the amount of rotation is directly proportional to the current passing through the conductor. This is the Faraday effect which is stated by the following simplified equation:

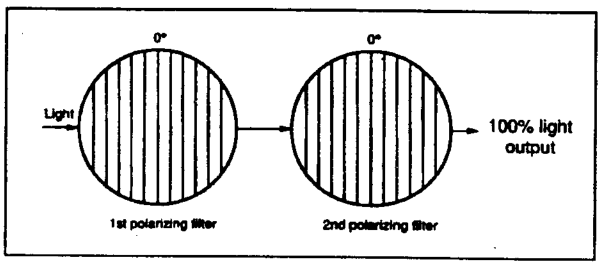
$$\Theta = VI$$

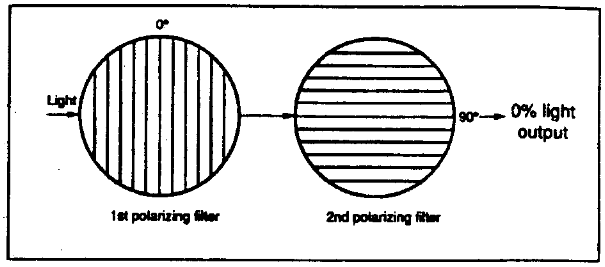
Θ = rotational shift in radians
V = Verdet Constant
I = current

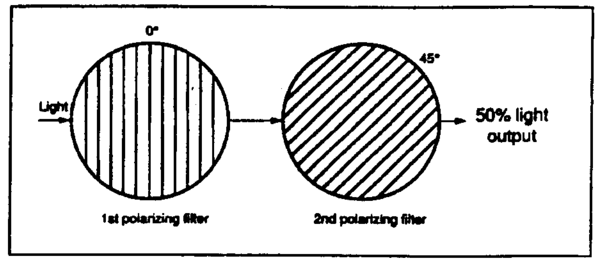
The analyzer which is a second polarizer, measures the amount of shift in the polarized light beam and translates the amount of shift into a corresponding amount of light intensity. The more current in the conductor, the stronger the magnetic field, the greater the angular shift in the polarized light. produces a more intense or brighter level of light passing through the analyzer to the optical electronics. The characteristic of two polarizers control the light intensity.

If the plane of polarization of two polarizers are rotated 90 degrees from each other, the light beam is blocked from passing through the second polarizer. Conversely, if the polarizers are shifted by zero degrees, then 100% of the polarized beam is transmitted through the second polarizer. So, half of the light beam's intensity or half of the amount of light will be transmitted through the analyzer when the two polarizers are rotated 45 degrees from each other.

The 45 degree rotation between the first polarizer and the second polarizer is the full scale reference point for maximum light intensity. As the light rays enter the polarizer at a zero degree reference, the Faraday effect will introduce an angular shift in the polarized beam. The greater the shift towards the 45 degree point of the analyzer, the greater the amount of light or intensity of light that will be transmitted through the analyzer to the optical electronics. Therefore, if the Faraday effect caused a 45 degree shift in the light beam, it would be the same as the zero degree shift between the two polarizers which would allow the full amount of light to pass through the second polarizer.







The following example illustrates the amount of rotational shift for a 50 kA fault.

$\Theta = V I$ $\quad\quad$ $\Theta = (0.31 \text{ x } 10\text{-}5)\text{x}50$ kA
$= 155 \text{ x } 10\text{-}3$ radians
$= 8.8$ degrees of rotational shift

Verdet Constants for Several Optical Glasses (Wavelength = 810 nm)

Glass Type	Verdet Constant (radians/amp turns)
SF-59	2.08 x 10-5
SF-58	1.86 x 10-5
SF-57	1.61 x 10-5
SF-6	1.39 x 10-5
SF-5	0.91 x 10-5
SF-2	0.84 x 10-5
F-2	0.77 x 10-5
BK-7	0.27 x 10-5
QUARTZ	0.31 x 10-5

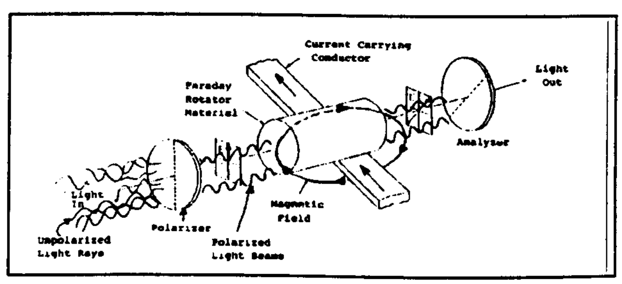


Figure 1

MOCT SYSTEM OPERATION

Figure 2 below shows the functional block diagram for the MOCT system. The LED provides the light source which is transmitted through the optical fiber link to the polarizer. After the light is polarized, it follows the optical path through the Faraday Rotator Sensor. As the light travels around the primary conductor through the Faraday Sensor, the plane of the polarized light is rotated by the magnetic field of the primary conductor. The light then exits through the analyzer which converts the amount of rotational shift into a proportional amount of light intensity. This intensity modulated light is conducted through a second optical fiber to a PIN diode. The PIN diode demodulates the light and after being amplified and filtered is a scaled voltage that represents the amount of current flow in the primary conductor.

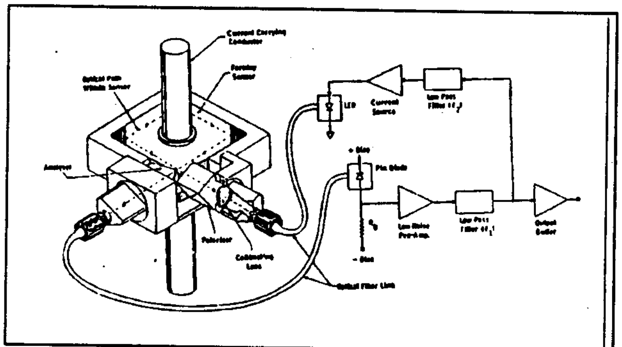


Figure 2

ADVANTAGES AND DISADVANTAGES OF MOCT METERING SYSTEM

The MOCT metering system offers many advantages over conventional current transformers, but introduces a few disadvantages because of the mixing of a new technology with an existing technology. Some advantages include:

- Provides optical isolation for safety.
  - no danger of open current circuit
  - inherently explosion proof
  - totally isolated from the primary conductor
  - no oil in the polymer columns

- Accuracy over a wide range of power system conditions.
  - no saturation under fault current
  - frequency range from 1HZ to 10KHZ
  - 0.2% accuracy from 20-4000 A
  - no ratio change required

- Light weight columns enable easier installation.
  - sensor head and column weigh about 350 lbs.
  - conventional CT's weigh about 9,600 lbs.
  - heavy duty crane equipment not required

- Cost savings of system at 345 KV.
  - MOCT metering package cost $70,000
  - Conventional oil filled CT's $96,000

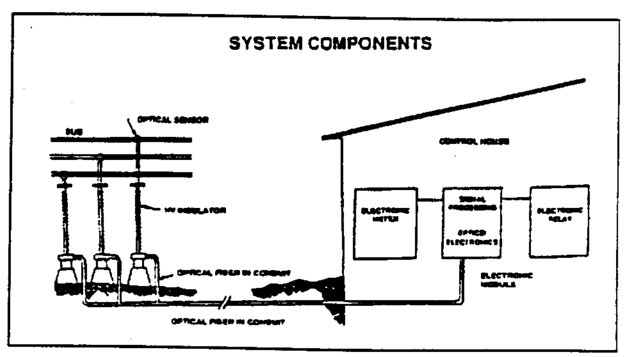
The MOCT technology introduces a need for change because of the merging of technologies.

- Optical system requires low power auxiliary equipment.
  - unable to drive 5 amp secondary current circuits
  - requires low power equipment
  - requires optical test equipment

GIBSON METERING APPLICATION

Recent problems with current transformers at Gibson Station provided PSIE an opportunity to apply a new technology to address the problem of catastrophic current transformer failures. The explosive failures of the 34509 metering current transformers presented a dangerous situation for personnel in the switchyard. One of the attractive features of the MOCT system is the safety provided by the optical isolation. Optical isolation, replacement cost, and accuracy made the MOCT a very good application at Gibson Station switchyard.

GIBSON METERING SYSTEM COMPONENTS



Optical Sensor

The sensor is located on the top of the high voltage insulator and weighs about two pounds. The sensor assembly contains the optical sensor of the MOCT. NEMA connectors link the sensor assembly to the primary conductor.

High Voltage Insulator

The light weight polymer column contains optical fiber that connects the optical sensor to the patch panel on the base of the structure.

Optical Fiber in Conduit

Each phase is routed to the patch panel and connected to the fiber optic cable which connects the optical electronics to the optical sensor. The sensor is located on top of the high voltage insulator.

Optical Electronics

There are two optical fibers per phase: one transmits the light to the sensor and the second is the return path to the phase card located in the optical electronics. The phase card converts the optical signal into an analog voltage signal that drives an electronic meter. Also, each phase card monitors the attenuation of the optical path for that phase. If the attenuation is out of limits, the red status LED will indicate an alarmed condition.

Electronic Meter

The electronic meter is the E1R bi-directional meter with the 2610 demand register. The meter counts the megawatt hour and megavar hour pulses to provide KYZ output pulses for billing purposes.

ACKNOWLEDGEMENT

Special thanks to the PSI Energy employees for their dedication and team effort in completing this project. Also, would like to thank the ABB personnel for their technical assistance in applying a new technology.

REFERENCES

1. Cease, Johnston, "*A Magneto-optic Current Transducer*" IEEE Transaction on Power Delivery, Vol. 5, No. 2

2. Maffetone, T.M. McClelland, "*345KV Substation Optical Current Measurement System for Revenue Metering and Protective Relaying*" IEEE proceedings April 1991

3. Johnston, "*Status of Optical Current and Voltage Sensor Research*" Edison Electric Institute T&D Committee

4. Udren, Cease, "*Transmission Line Protection with Magneto-Optic Current Transducers and Microprocessor Based Relays*" Georgia Relay Conference, May 91

A Primer on Optical Current and Voltage Sensors and an Update on Activity

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Division of Laboratories

Abstract - As optical communications found its way into the norm due to unique abilities, optical sensors will eventually be the preferred technology used to measure powerline parameters. The basic designs of several types of active and passive voltage and current sensors are discussed as well as the means used to apply them to the power system. An overview of commercially available systems is provided as well as a discussion as to some of the reasons they are not in place as yet.

Introduction

Of the "for sure" things that we must depend on happening whether or not we are ready for or even want; are death and taxes. Add to the list, "new technology will replace old technology". New technology, its scope here being the integration of optics and computers in advanced power system circuit designs, presents a way to provide for critical changes in operation techniques. These changes will provide for system optimization and modifications to be made rapidly and with the highest confidence. Gone are the days where electronics will be specified for lifetimes in excess of 20 years because modular techniques will allow for instant computer certified solutions and system changes based on past information and our ability to interpret and understand that information.

To understand the power system (or for that matter, any process), you must take data and turn it into information. This is where sensors come in. Sensors connect to the power circuit to acquire data, or more accurately, provide a representation of that parameter for remote analysis. The better the data, the better the ability to make wise operational decisions and about what can be improved. Ideally, these measurements must not disturb the circuit and the circuit must not disturb the data. Past sensors (e.g., transformers, transducers) were expensive and post-event analysis tools were not actually on-line and a matter of course. Because of the capitol expense involved, required changes could be made, but desired changes, those with marginal, but evolutionary improvements, often waited until equipment obsolescence came around. Optical sensors and electronic computers will be modular and important designs will allow for modifications almost at will.

To properly operate a power system circuit, there are at least two essential tasks required; the measurement of power for revenue metering and measurement for protection of that circuit. Both require knowing the voltage and the current on the circuit as well as the time frame involved. Current and voltage measurements are data, and when converted into a form that the measurement electronics can understand (this would include applying scaling, calibration and other factors), it is information. And when converted into power relative to time (i.e., watts, vars), it is knowledge. Wisdom is the final step and determines if the method used is the best in terms of engineering and economics. For example we can always increase the resolution of the data but would the increased investment provide a

Prepared for the 1992 Engineering Symposium
Bonneville Power Administration
March 31 to April 1, 1992
Portland Oregon

economic benefit in return? Questions as this, determine the value of modularity.

In the past, the implementation of computers and other electronic systems into the process have allowed us the ability to balance specifications with economics only to a point, as the sensors used were not actually compatible and thus not flexible. The need for what has been called "low energy" sensors has been bolstered by the growing stable of optical tools born out of the communications industry.

So because of the ability to connect directly to the power line, the modularity, the promised increase in resolution, the lower costs and the compatibility to solid state electronics, optical sensors will certainly be the means used to acquire data from the power system in future designs. The discussion here is on both active and passive optical voltage and current sensors.

Overview of Sensor Requirements

To provide for the two tasks necessary in operating a power system; revenue metering and circuit protection, a basic understanding of the requirements is needed. To do this, it is not really necessary to copy conventional sensor specifications exactly, as many terms and conditions do not relate or even apply to optical sensor technology. For example the inherent non-linearity of conventional transducers and their sensitivity to load, requires rather complex specifications. Optical sensors (current or voltage in this discussion), being rather linear in nature and insensitive to load, can be specified as a simple deviation from a straight line fit and is known as "uncertainty". The word Burden, will not exist in the optical sensor world and neither will be the requirement of 5 amp and 220 volt output levels. What will be important will be the signal to noise ratio of the sensor, the ability to preserve the phase angle (or time relationship) between other measurements on the circuit. Also saturation need not be an issue with conventional sensors, but passive optical sensors can be designed not to saturate (more on this later).

In order to determine the best possible fit between the lowest achievable uncertainty (or resolution) and the costs necessary to obtain it, a great deal of work has been done to identify possible error terms that will be present. To best insure that optical sensors will be at least as good as the technology they will replace, several basic assumptions were made on the outset which are summarized in **Figure 1** below: The charts show approximate ranges and values due to the fact that there will be

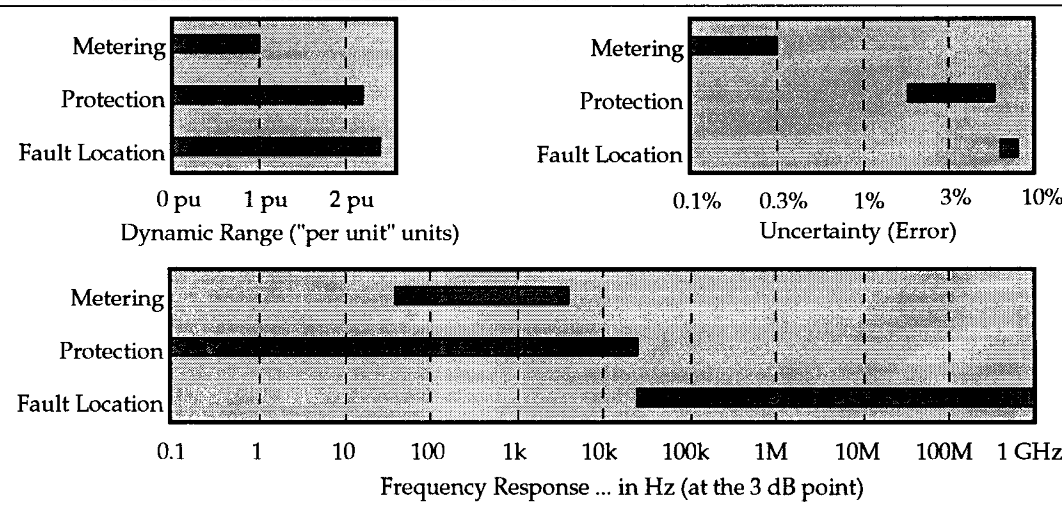


Figure 1 - Generalized Sensor Specification Summary

some leeway in system design as the sensor/ interface configuration matures. At this time, there is great flexibility in the concept making it possible to fine tune requirements along the way.

Note the addition of a third consideration, *Fault Location.* This is included here because, while not directly related to circuit protection, is related to the time it takes to bring a system back into operation after a system disturbance that would cause a temporary or permanent fault. A concept used to extend BPA's timekeeping skills to the microsecond level (known originally as Microtime) [1-3] allows for the use of synchronized counters or clocks and high frequency optical sensors to allow automatic and instant location of faults to within one tower on overhead lines and to within one meter in compressed gas networks. As Microtime was also developed as a means to allow for advanced phase angle telemetry (to a theoretical accuracy of 22 millidegrees), specialized salient features inherent with optical sensors (such as very fast response time) are important to the logical advancement in this area. In addition the use of technology in this range allows for research equipment designs that are used for further system optimization studies.

The following discussion deals with optical sensors and techniques and includes a sampling of systems available at present.

Optical Sensor Types

There are two distinct classes of optical sensors; *Active* and *Passive.* Active sensors use conventional transducers coupled to on-site electronic to optical converters powered in some way by local energy conversion elements. This class makes use of some excellent conventional transducers that were not practical before without modern optical transmission means. Passive sensors, on the other hand require no electronics or power supplies at the measurement site and use long understood physical techniques to convert current or voltage (or the fields caused by them) to provide optical modulation. The transmission path in both cases is fiber optic and path lengths may extend to immediate ground level, or directly to the control house that could be many kilometers distant.

Active Sensors

The most common conventional methods used in measuring current and voltage on a high voltage conductor are by iron core (current) and capacitive potential (voltage) transformers. The main problems, especially with current transformers, are cost (most of the cost is in the insolation and porcelain required), their nonlinearity and saturation. With current transformers, there is the additional risk of explosion due to the build-up of hot gases in a vessel not adequately designed for pressure relief.

Before the days of optical isolation there were few suitable methods to do the task any better. With the ability to optically isolate, thus requiring less insulation and therefore less costly, other current measurement methods could be used. Two of the best methods for measuring current were Rogowski coils and current shunts (in-line resistors). Inexpensive and more accurate, they could be placed around or in the conductor and because both provide a low level voltage relative to the current, that signal could not be brought to ground with conventional techniques.

Voltage measurement using capacitive or resistive dividers could also be optically isolated at the ground level at lower costs if the stringent burden requirements could be relaxed.

This next section will provide insight on two of the problems associated with designing active optical sensors. These problems are;

powering the electronics and which method would be used to encode the light beam.

Types of Active Sensors

Current Measurement Using Active Sensors

Several methods are presented below that have or could be used with an optical transmitter for the measurement of current in a high voltage transmission or distribution conductor:

- Resistive Shunt (or Current Mirror) - A high power, very low value (typically 50 μΩ) resistor inserted in series with the conductor will provide a voltage proportional to the current in that conductor. The design is inherently simple with the drawback being the need to insure that the maximum power dissipation will not exceed the resistor's specifications. Also these units are good only into the tens of kHz (however, more than adequate for protection schemes.) We have used this technique quite often at BPA especially in staged fault tests both on the ac and dc lines [4-7].

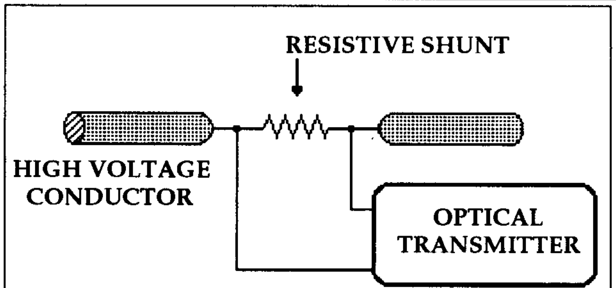


Figure 2 - Resistive Shunt Application

- Iron Core Transformer (CT) - Using an iron core with the primary "winding" being the conductor itself, would provide a mirror of the conductor current with low costs (certainly compared with the type of CT's used today) but the problems with saturation and non-linearity would still persist. The possibility of retrofitting existing CT's does exist with this method. BPA has experience in this area [7,8].

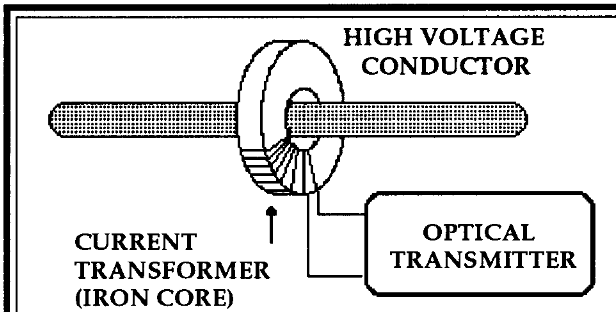


Figure 3 - Iron Core Transformer Application

- Air Core Transformer (or most commonly referred to as a Rogowski Coil or linear coupler) - Saturation is not normally a problem with this approach and the costs are low. This approach has been used successfully at BPA both in monitoring very high currents (100 kA on a steel mill furnace feeder) [7] and very low currents (less than 10 mA monitoring harmonics at Celilo).

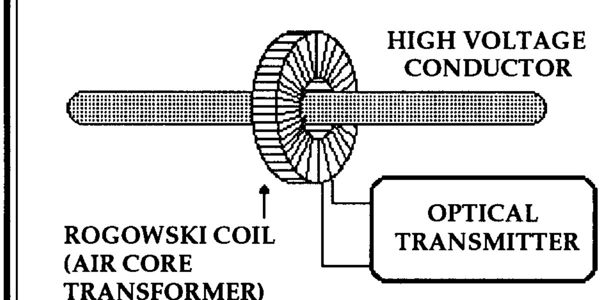


Figure 4 - Rogowski Coil Application

For the record, a Rogowski coil based system, powered by an iron core transformer that uses microwave linking is available from Nitech of Fairfield Connecticut, that has been tested at BPA. It measures the voltage, current and temperature of the line and is particularly useful in measuring line sag.

Voltage Measurement Using Active Sensors

Several methods are presented below that have or could be used in the measurement of voltage on a high voltage transmission or distribution conductor:

- Stepdown Voltage Transformer (VT) - This approach, differs in the conventional way in that coupling is done optically. The design of the transformer and the line to ground insulation could be less costly than using transformer coupled means. The optical transmitter could reside at the high voltage end if necessary.

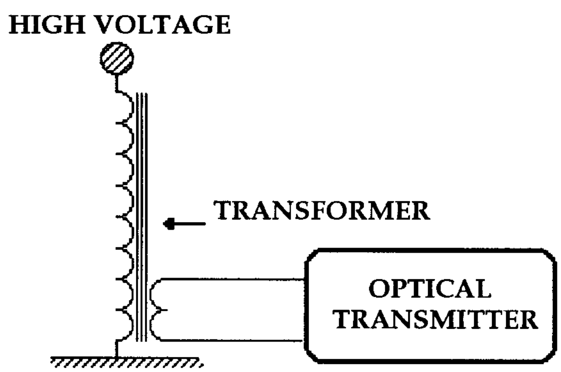


Figure 5 - VT Application

- Capacitive Potential Transformer (CPT) - Same comments as with the VT discussed above but a more commonly used transducer. Retrofitting existing CPT's could easily be done and in fact has been explored here at BPA, especially as a fault transient detector.

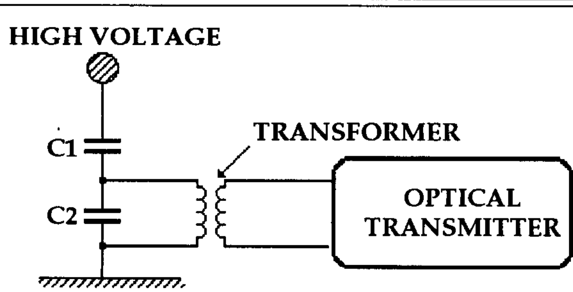


Figure 6 - CPT Application

- Resistive Divider - Again, same comments as above, but there are salient features including lower costs and versatility.

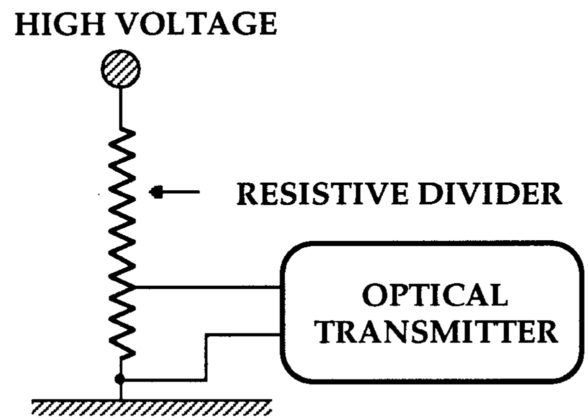


Figure 7 - Resistive Divider Application

- C2 Section Divider - Using a capacitive plate in series with the natural capacitance that exists between it and the conductor, provides the best approach when measuring gas insulated systems which have very high frequency components (<1ns risetimes). This also has been done at BPA [9].

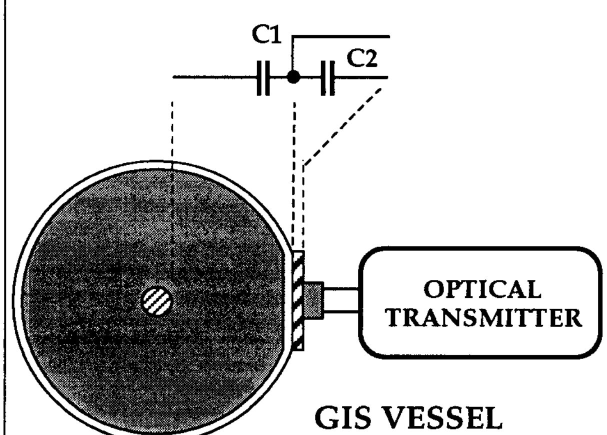


Figure 8 - C2 Section Application

Remote Power Supply Methods for Active Fiber Optic Sensors

Since an active sensor requires electrical power at the conductor level there are several methods that have or could be used in powering the electronics module. The following list provides some short comments on a few of the most interesting methods:

- Batteries - Even with modern chemistries, they must be serviced often and most power utilities will not allow this.
- In-Line Current Transformer - Used if the conductor current always present, but if it is ever off, then backup batteries must be used (see above comment).
- Resistive Shunt - Same problems as the In-Line Current Transformer.
- Solar Powered - Used, but because of the need for batteries, a poor choice. This method suffers also because of inherent exposure of the plates to the elements and to vandals.
- Piezoelectric - By using a dielectric rod to couple two piezoelectric crystals, power transfer can be done. A good method, but not used much.
- Rotating Dielectric Rod Coupling a Motor and Generator - As with the piezoelectric method, good but not used very much anymore, only here there is something to wear out.
- Wirewound Isolation Transformer - Used more often than most other methods, but is very expensive and bulky.
- Laser Powered - Using a ground based laser beam coupled to a fiber (possibly the same fiber bringing down the encoded information) and a measurement site located photodiode; power transfers up to 50% are possible with no need for battery backup. Only recently possible, this method is the best as it fairly inexpensive (all things considered) and reliable.

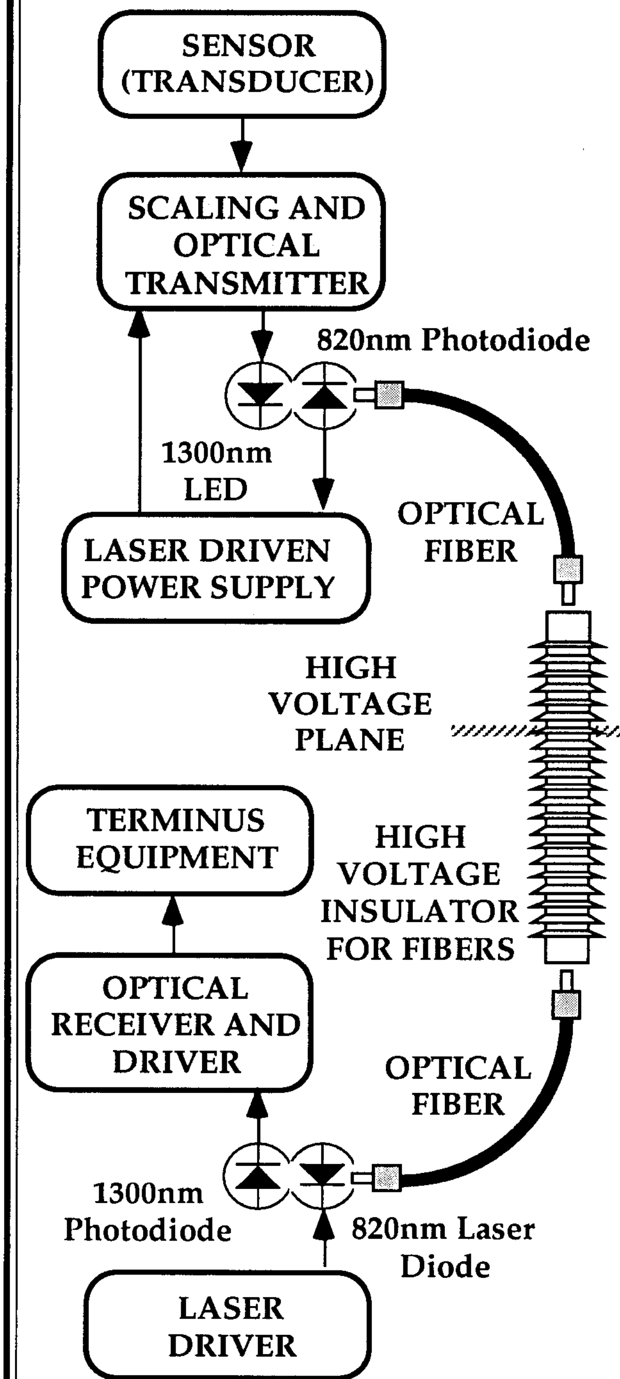


Figure 9 - Optical Powered Transmitter Application

Note that in the above Figure, the laser and the photodiode at the bottom and the photodiode and the LED at the top are combined. This is possible because the uplink is operating at an optical wavelength of 820 nm and the downlink is at 1300 nm. Since both the laser and the photodiode are transparent to the 1300 nm wavelength, they can be manufactured behind the 820 nm elements. This scheme only uses one fiber.

Encoding Methods For Active Fiber Optic Sensors

There are two methods commonly used in modulating a light source; analog and digital. And there are two digital types, AD/DA and VF/FV.

- Analog (or most often referred to as intensity, modulated) - By varying the current directly through an LED or laser diode, data can be converted from electrical to optical for passage to a remote receiver using fiber optics. This method results in the lowest component cost but does have several limitations. The first being that it is slightly non-linear. Also this method consumes a lot of power and has a limited dynamic range. The primary advantage aside from cost, is its ability to work at very high frequencies (at BPA we have designed systems that go into the GHz range [9]). The best application for these sensors is in self powered designs, measuring voltage or events that require low resolution (as in fault detection).

- Analog to Digital/Digital to Analog - This method, on the surface would be the best as the conversion would most certainly be compatible to the digital analysis system it would connect to. The costs are moderate and 500 ksample rates at 16 bits is possible, but the transmitters are usually power hungry and complex. Dynamic range would not be a problem if using 16 bit conversion (one part in 65K) electronics.

- Voltage to Frequency/Frequency to Voltage - As of now the most preferred, as the transmitter is simple and, compared to the A/D converter, needs much lower power requirements (for a 10 kHz bandwidth system, 3 mW has been achieved). High bandwidths are possible but the resolution is compromised. Still this is the best choice for most applications requiring low power, high reliability systems. The most severe drawback is that after conversion from optical to electrical, a second conversion from frequency to digital is necessary. BPA has used this method extensively for over 15 years in many measurement applications and it is the main means used in the BPA Test Trailer [4-8,15-17].

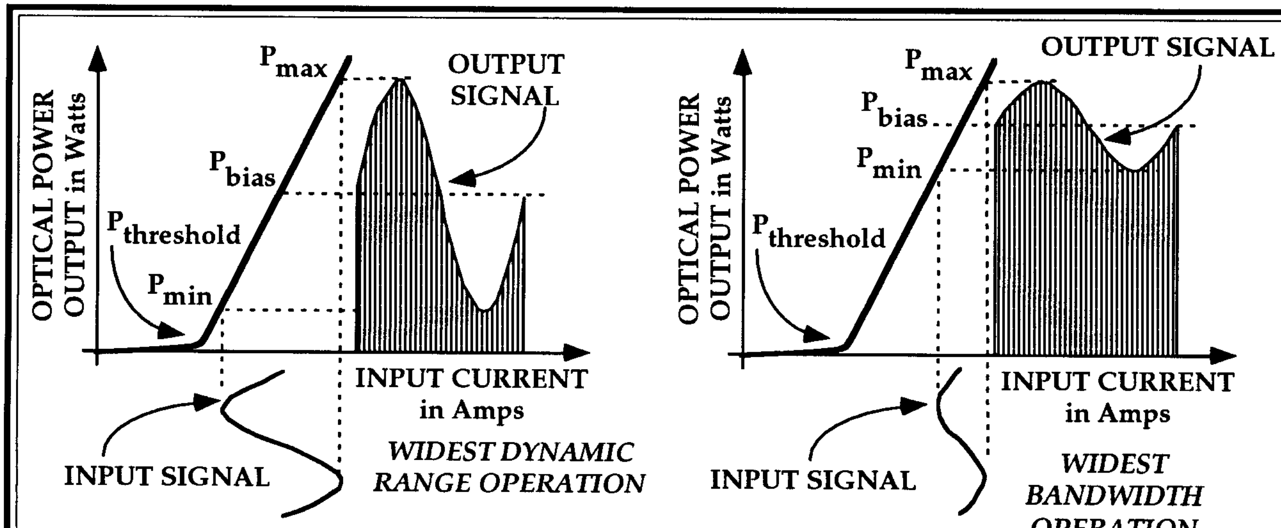


Figure 10 - Intensity Modulation Methods

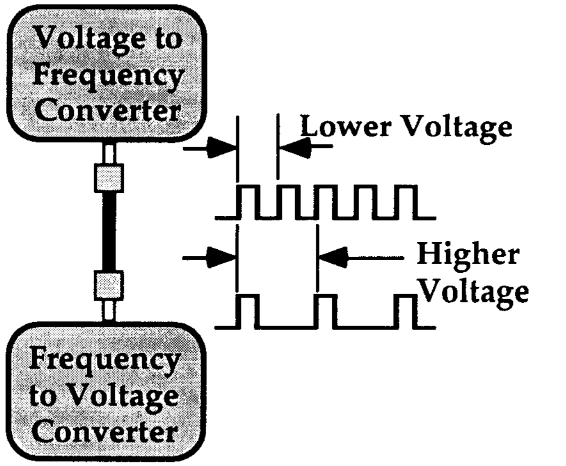


Figure 11 - Block Diagram of a V/F to F/V System

Passive Sensors

In an ideal design there would be no electronics at the measurement site and by using several interesting physical effects this is entirely possible. Such designs would incorporate pure optics, would have no saturation problems and would allow for minimum conductor to ground isolation. They need not be dependent at all to conventional sensors and in fact the sensor itself may be intrinsic to the communications medium. A great deal of effort at BPA has placed in the identification of the possible error mechanisms and the techniques to be used to connect a passive sensor to the power system [10-14].

Optical sensors can be made to measure any physical phenomena and hundreds are now available. To measure current and voltage, two principles have been isolated with a variety of configuration designs.

Figure 12 shows the general diagram for the type of optical sensor in discussion. Note however that many configurations exist including those that are intrinsic (the witness material is in fact the fiber itself). In addition there are other methods that split the exit polarized beam into three components. As will be shown later, there are ways to analyze the modulated signal using only one of the two exit beams shown in the figure.

Current Measurement Using Passive Sensors

The principle used most commonly to measure the current is the *Faraday Effect.* In 1845 Michael Faraday discovered that under the influence of a magnetic field, glass becomes optically active. This activity can be witnessed using a linearly polarized light beam which will rotate as a function of the magnetic field, a special "constant" relative to the type of glass used, the wavelength of the optical source and the length of that glass.

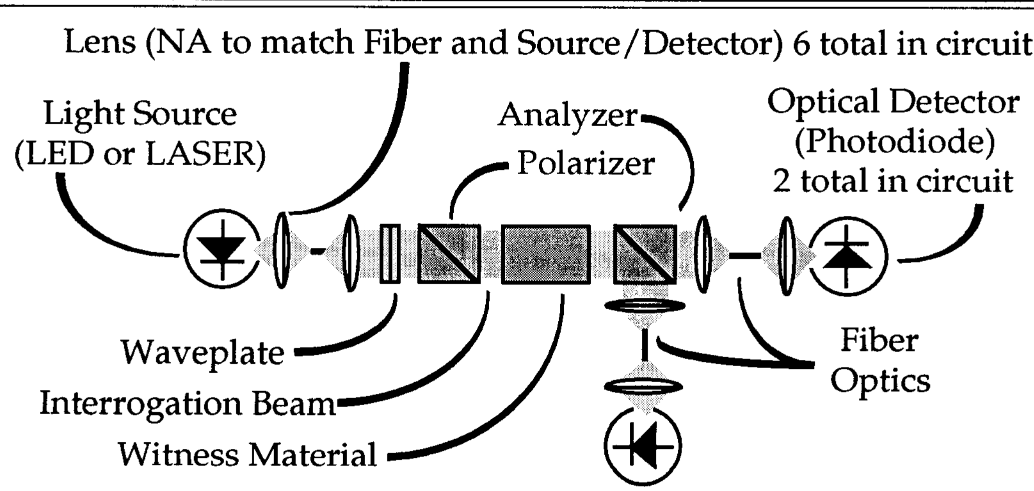


Figure 12 - Optical Block Diagram of an Optical Sensor

This rotation is given as:

$$\delta\theta = V\oint_0^L \bar{H} \bullet d\bar{l} \qquad \text{Equation 1}$$

where:

θ = The Polarization rotation
V = The Verdet constant (actually not a true "constant" as it is sensitive to the wavelength of the source and the temperature of the glass)
H = The Magnetic field intensity
L = The Optical path length (note that this effect is nonreciprocal, that is the rotation "builds up" even if it is reflected back down the optic axis (the path can also "zigzag" down the optical axis thus increasing the overall length and thus the sensitivity)

From this equation it can be shown from Ampere's Circuital Law that:

$$\theta = V I n \qquad \text{Equation 2}$$

where:

I = The current in the conductor (assumes that the total field around the conductor is monitored)
n = number of turns around the conductor
V = The Verdet constant (in Radians/Turn-Amps)

If the sensor monitors the field density in some defined space away from the conductor then:

$$\theta = V B L \qquad \text{Equation 3}$$

where:

B = The Magnetic flux density
V = The Verdet constant (in Radians/Gauss-cm)

Current Sensors using **Equations 2** and **3** as a basis are classed into three types; *the Bar*, the *Ring* and the *Fiber* sensor configurations:

- Bar Sensor - In this approach a Faraday glass is placed longitudinal to the B-field and optical rotation can be monitored as shown in **Figure 13**. This approach is not the most accurate of the three, because it does not encompass the conductor so it is sensitive to the B-fields, but is the only one that can easily be attached to the line without disconnecting the circuit. By using a concentrator made of iron or Metglas(see **Figure 14**), amplification is achieved but at the price of saturation and frequency response.

BPA [12,14], Square D [18], Optra [19] and Sumitomo [20,21] have made such concentrator systems and other interesting work is being done in Denmark and by other companies in Japan. The Sumitomo system is still in production after 10 years, but due to the poor accuracy (±2% from 0 to 40°C) it is still used mostly in the lab. Its strong points, beside being able to clamp on to the conductor, is that it is simple to manufacture and thus can be very inexpensive. Use **Equation 3** for this type.

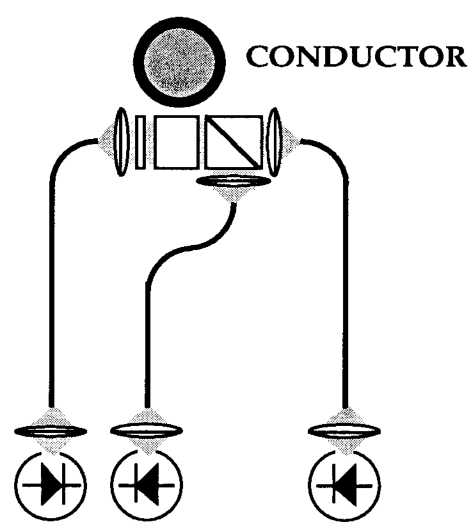


Figure 13 - Schematic of a Bar Sensor

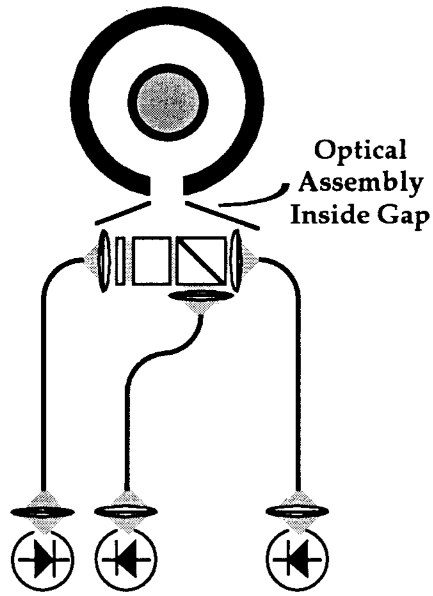


Figure 14 - Schematic of a Bar Sensor with a Concentrator (note that in actuality there is a small gap in the core where the optical assembly is placed)

• Ring Sensor - By creating a full turn around the conductor with bulk glass (**Figure 15**), this sensor is immune to other fields. Drawbacks are that is difficult to manufacture and stresses in the glass ring introduce unwanted optical modulation effects into the system increasing the error. But, with careful design and manufacturing, this method has provided accuracies that meet or exceed conventional systems.

Many commercial systems exist and have been through field trials. The most notable is the ABB system [22] (formally a Westinghouse effort) which has been installed for many years in the 161 kV Chickamauga Dam switchyard. This was a metering grade system that performed very well. Square D also manufactures a system that uses this approach [18,23]. Also Toshiba Corporation has tested systems at the Tokyo Electric Company that uses this approach to monitor a GIS (Compressed Gas Insulated) installation [24]. Still another GIS system is the Hitachi sensor [25]. Use **Equation 2** for this approach.

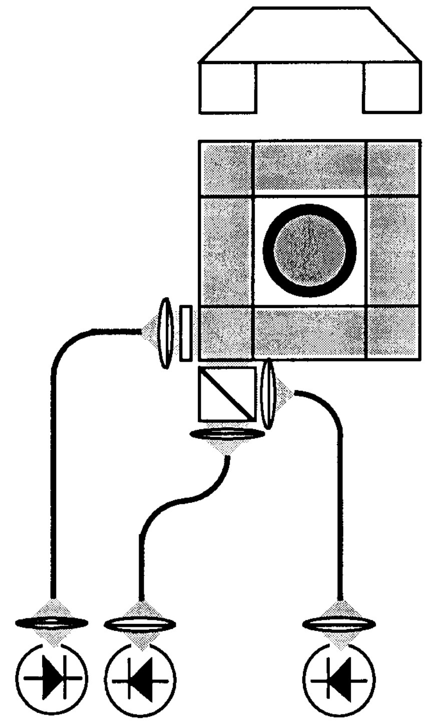


Figure 15 - Schematic of a Ring Sensor (note that some manufacturers cement four blocks together while others make it out of a single piece of glass)

• Fiber Sensor - Both of the previous systems are extrinsic sensors. The fiber sensor is intrinsic as the fiber itself is the sensitive element. The ability to use the fiber as a sensor makes potentially the most economical sensor of the three but until recently stresses introduced when bending the fiber, were overwhelming. But techniques involving heating the fiber in its form and annealing it almost eliminate these problems [26]. Eventually this approach should dominate and provide for the most accurate and less costly of the methods and more than exceeding todays current measurement specifications.

Available systems include the PSC Enertec system trialed at EDF in France [27], the 3M system under development at present [28] and the Sifam system [29] (of England). Each system uses a different approach as shown in the following figures.

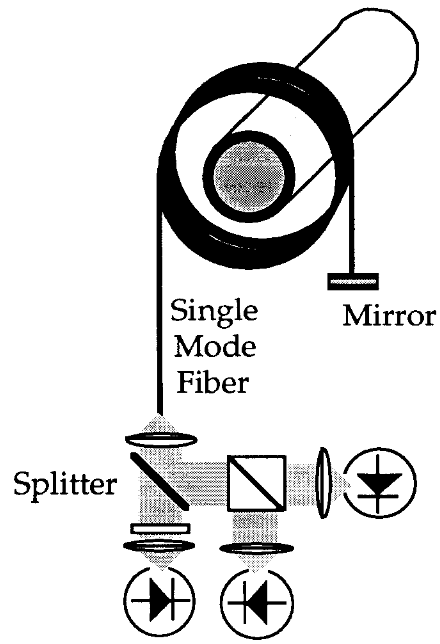


Figure 16 - Schematic of PSC Enertec Fiber Sensor (note that the light is redirected back through the fiber to help cancel out birefringence effects)

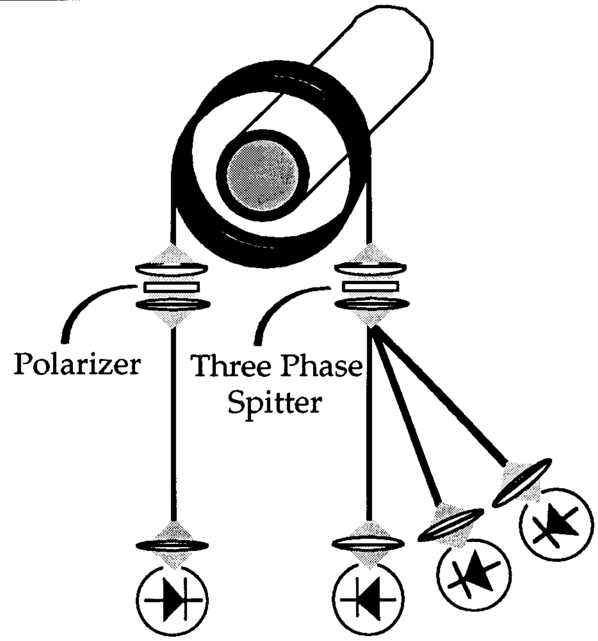


Figure 18 - Schematic of the Sifam Limited Sensor (note the use of three beams as there is a special compensation scheme that will increase the dynamic range and correct certain light level variations)

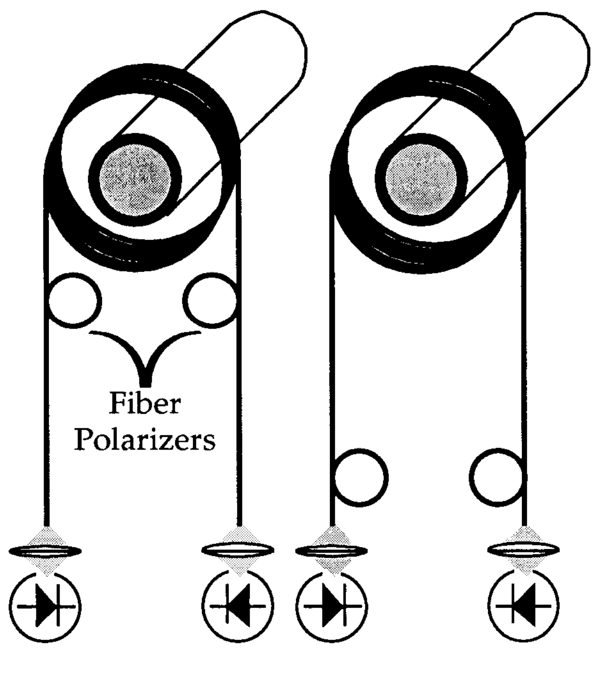


Figure 17 - Schematic of 3M Fiber Sensor Showing Two Possible Versions (note that the polarizers are in fact fibers)

<u>Voltage Measurement Using Passive Sensors</u>

To measure voltage on a conductor, we use a principle known as the *Pockels Effect*. This effect, while similar to the Faraday Effect, differs in that the polarized light is circular and the electric field causes the beam passing through a special crystal to force a phase shift relative to both orthogonal axes.

In 1893, Friedrich Pockels discovered that under the influence of an electric field, certain crystals (those that lack a center of symmetry) are birefringent, that is, having differing optical velocities in both orthogonal axes as a function of that field. This activity can be witnessed using a circularly polarized light beam which becomes elliptical as a function of the electric field, special "constants" relative to the type of crystal used, the wavelength of the optical source and the length of that crystal.

This activity known as retardance is given as:

$$\Gamma = 2\pi n_o^3 r_{u,k} LE / \lambda \qquad \text{Equation 4}$$

where:

- Γ = The Retardance (in radians)
- n_o = Ordinary index of Refraction (no dimension)
- $r_{u,k}$ = The Electro-Optic constant (in meters/volt)
- L = The length of the optical axis (in meters)
- E = The electric field (in volts/meter) note that some crystals are used in the longitudinal mode and some are used in the transverse mode
- λ = The wavelength of the light source (in meters)

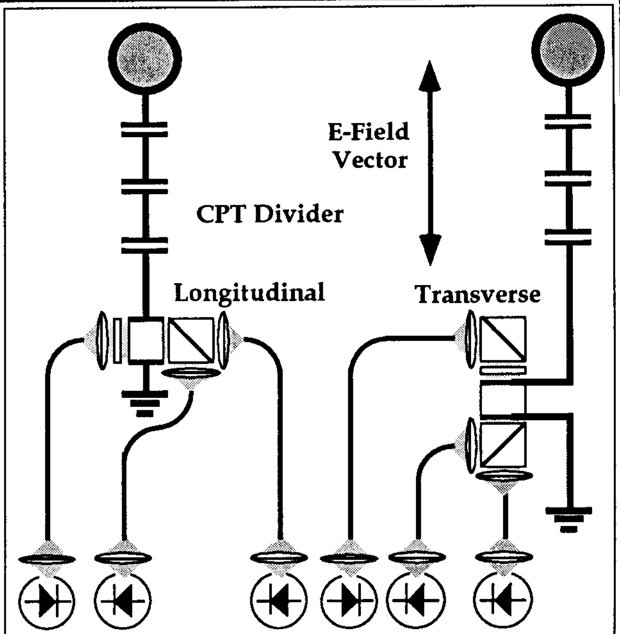


Figure 19 - Schematic of Two Versions of Contact Sensors)

The measurement of voltage is a bit more involved as the potential must be relative to ground. To measure voltage using the Pockels effect two approaches have been studied:

- Contact Sensors - A Pockels crystal requires a voltage placed either longitudinal or transverse to the optic axis (**Figure 19**). Using a voltage divider (as those described above) this is readily achieved. The problem is one of possible breakdown and the added expense of the divider. Manufactures include PSC Enertec [27] (integrated with the current sensor described earlier), Hitachi, (both using a CPT as a divider) and Sumitomo [20,21] (having free leads capable of a 500 v input).

  A very interesting approach to this problem is being tested at the Technical University of Denmark (DTH) using a special GIS design. Here a capacitive divider, unlike a conventional CPT is used as shown in **Figure 20**. The voltage sensor is one manufactured by Sumitomo.

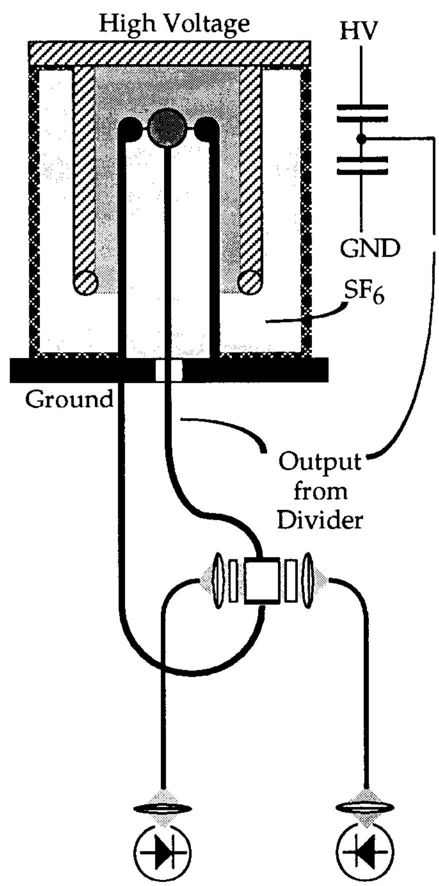


Figure 20 - Schematic of the DTH Approach

Along the same lines is a special technique which is also phase related. Interferometric means can be used to design more sensitive sensors that can be used in a variety of ways. Using the Mach-Zender Interferometer (MZI) as shown in **Figure 21**, other configurations exist.

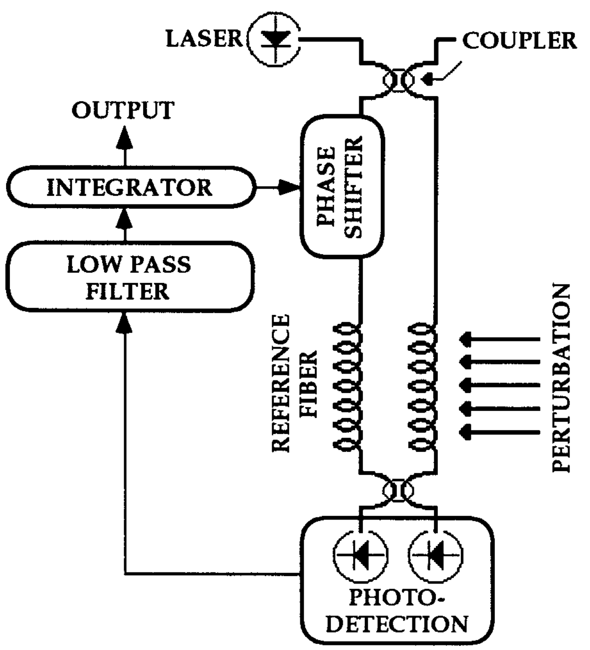


Figure 21 - Schematic of a MZI (the fiber being disturbed can be connected mechanically or electrically to the perturbing signal)

Optech of Herndon, Virginia, markets a MZI system that uses a CPT divider that couples to a piezoelectric cylinder that has the sensor fiber wrapped about it [31]. In fact using a Rogowski coil coupled in the same way, current can be measured using exactly the same elements. This is an important step in insuring that the next generation of sensors is modular.

- Field Immersed Sensors - By immersing the sensor in a tightly controlled E-field, measurement is readily achieved. The main drawback is designing the cavity to be impervious to external fields and temperature variations. By using techniques learned in the design of gas insulated substation apparatus, such designs should not be a problem.

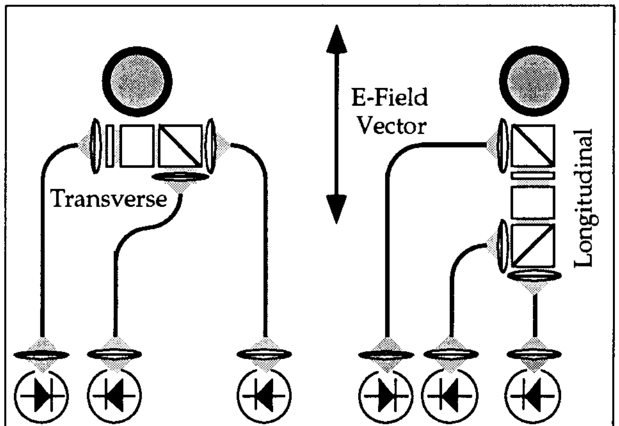


Figure 22 - Schematic of Two Versions of Field Immersed Sensors

<u>Measuring Voltage with Current Sensors and Measuring Current with Voltage Sensors</u>

There are some clever means to use the sensors described previously to measure other quantities. A few are shown below:

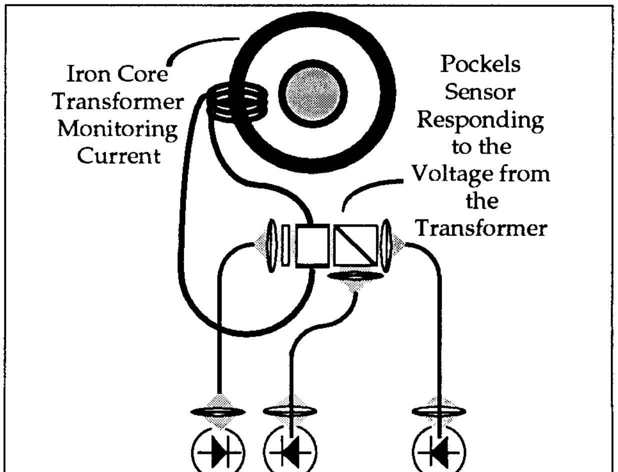


Figure 23 - Schematic of a Current Measurement Sensor Using a Pockels Sensor

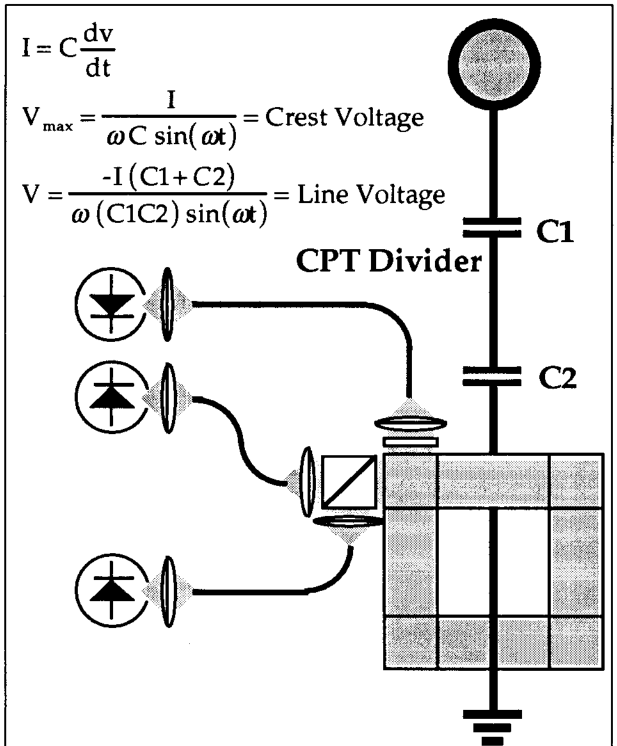


Figure 24 - Schematic of a Voltage Measurement Sensor Using a Faraday Sensor

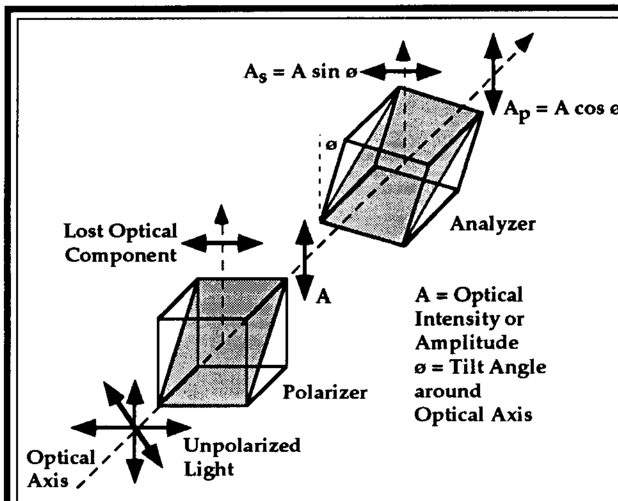


Figure 25 - Polarizer/Analyzer Relationship

The Sensor Interrogation Process

Referring back to **Figure 12**, note that one beam is used to interrogate the sensor and two beams provide the end result. In addition a waveplate is necessary to prepare the input beam. The reason this works and an explanation on why a waveplate is required is the basis of the following discussion.

As it is not possible to directly detect the polarization angle of incident light using a photodiode, the interrogation beam, modulated by the sensor material, must be converted into two (or more) intensity beams. This is conventionally done with an analyzer placed relative to a polarizer as shown in **Figure 25.**

In a normal situation two orthogonal vectors are created as shown. Note that there is an intensity vector "A" and an angle "ϕ" which is the angle difference between the polarizer and the analyzer. The resultant vectors would be given as:

$$A_p = A\cos\phi \qquad A_s = A\sin\phi \qquad \text{Equations 5 and 6}$$

From the law of Malus, which states that the transmitted optical intensity (e.g., amplitude) varies with the square of the cosine or sine between the two planes of polarization, the transmitted optical power is then:

$$P_p = P_{in}\cos^2\phi \qquad P_s = P_{in}\sin^2\phi \qquad \text{Equations 7 and 8}$$

Then including the optical modulation ("M") due to the sensor material (note M = θ for a Faraday sensor, M = Γ for a Pockels sensor):

$$P_p = P_{in}\cos^2(\phi + M) \qquad P_s = P_{in}\sin^2(\phi + M) \qquad \text{Equations 9 and 10}$$

where:

P_{in} = The optical power input (note that losses need to be taken into account).

Both can also be expressed as:

$$P_p = P_{in}\cos^2(\phi + M) = \frac{P_{in}}{2}\left[1 - \cos 2(\phi + M)\right]$$

$$P_s = P_{in}\sin^2(\phi + M) = \frac{P_{in}}{2}\left[1 + \cos 2(\phi + M)\right]$$

Equations 11 and 12

The next step is to determine the value of "ϕ" so that when the modulation is zero, there will be an equal distribution of light between "P_p" and "P_s". For the Faraday circuit, we know that since "M" is a rotation, making "ϕ" 45° or $\pi/4$, **Equations 11 and 12** will be equal when "M" = 0.

There are actually three ways to do this (refer back to **Figure 12**). The first is to actually rotate the analyzer (or polarizer) 45° around the optical axis. The second is to rotate both, one clockwise and the other counterclockwise 22.5° off optical axis. The third would be to use a *half waveplate* which has the property of allowing a rotation at any angle. This feature would allow for "tuning" the optical balance in manufacturing, possibly reducing costs, however the problem is that waveplates are expensive and temperature sensitive so that little is gained. Inserting "ϕ" = $\pi/4$ into **Equations 11** and **12**, we get (after the trig is done and making "M" equal to "θ"):

$$P_{p,s} = \frac{P_{in}}{2}(1 \pm \sin 2\theta) \qquad \text{Equation 13}$$

As for the Pockels sensor, which is phase modulated, the we must cross the polarizer and the analyzer ("ϕ" = 90° or $\pi/2$) and add an additional bias to "M" (which in fact acts like a variable waveplate) so as to create optical balance when "M" = 0.

Making the waveplate element add an additional 90° to the circuit would result in the following (making "M" now equal to "Γ"):

$$P_{p,s} = \frac{P_{in}}{2}(1 \pm \sin\Gamma) \qquad \text{Equation 14}$$

This kind of waveplate is known as a *quarter waveplate* and produces circularly polarized light.

Note that the same electronics for each sensor are used at the ground level which allows for a universal design.

Fiber Optic Types for Faraday Sensors

In theory a single-mode fiber is supposed to allow propagation of linearly polarized light along the entire path. However it is extremely difficult to fabricate them as perfect cylinders and to be impervious to external perturbations such as stress, temperature effects, etc. Conventional single-mode fibers used in the communications industry need pass only intensity modulated light, so for those applications, polarization maintenance is not a problem (note however that it will be important with the next generation of communication systems). To launch polarized light into these fibers would result in the orthogonal components having differing phase velocities which is known as linear birefringence. This would in effect, disturb any Faraday rotation measurement.

To make fibers that could be used in intrinsic configurations that use no imaging elements such as lenses (See **Figure 12** for an extrinsic sensor, **Figure 17** for an intrinsic type), fibers with very low birefringence or those with very high circular (or elliptical) birefringence are needed. The idea in using the latter would to be average out the linear birefringence over the active path and in addition the internal static birefringence would be much higher than what could be dynamically applied externally.

Twisting the fiber can average out the linear birefringence but this is very hard to do without breakage. Spinning the fiber during manufacture has provided fibers with very low internal birefringence and have been used in several Faraday sensor systems. The problem is that the external effects such as bending and pressure must be eliminated in the sensor design. Another method used in reducing the bend-induced birefringence in fibers is to form a coil, heat it up to about 800°C for a period of days and anneal it by slowly cooling. These fibers are now available and show promise in mass-produceable designs[26, 28]. Finally, producing a fiber that is highly circular birefringent, would be relativity independent to external linear birefringent activity. Such fibers are made by having the core follow a helical path down the optical axis bounded by the cladding or by twisting it as described before.

Materials Used in Optical Sensors

Most of the success in the design of extrinsic optical sensors is in witness material selection. For the Faraday sensor there are three types of glasses; paramagnetic, diamagnetic and ferromagnetic. If temperature sensitivity is an issue, then the choice is diamagnetic. But if very high measurement sensitivities is required, and temperature can be controlled, corrected for, or is not an issue, then paramagnetic or ferromagnetic materials are more sensitive, with the latter far more so but then saturation becomes an issue. Materials of importance are SF-57, SF-6, SiO_2, BK-7 and ZnSe (diamagnetic) and YIG (yttrium iron garnet) (ferromagnetic).

For Pockels sensors the selection is more involved as many material selections exist. The most important feature is the temperature insensitivity and (from **Equation 4**) the product n^3r (one figure of merit used). Important materials are $Bi_4Ge_3O_{12}$ and $LiNbO_3$. For high sensitivities KDP has a high figure of merit but is somewhat temperature sensitive. There is a special electro-optic plastic (EOP) that shows promise especially for very low cost designs that is being investigated at present.

The key point here is, given the fact that the sensor will be temperature sensitive (due not only to the witness material but also to alignment and other factors) compensation of some sort may be necessary to mass produce inexpensive designs, especially those to be used in distribution applications. To date little attention has been given in the area of dynamic temperature compensation, but given the ability to measure the temperature with optical means and the fact that computers will surely be used in the analysis procedure, costs in integrating temperature compensation could outweigh costs in providing temperature insensitive systems.

Identification of Problems and Compensation Techniques

It would not be fair to present this topic and not list some of the assorted problems that had to be solved to make this technology available to the power measurement industry. The following are just a few of these problems and solutions:

- Review of **Equations 13** and **14** indicates there will be distortion as modulation extends beyond certain bounds. Although this looks like a non-linearity problem, it is in fact quite predictable and there are several means that can easily correct for it:

  Solution 1 - Use lookup tables if digital analysis is done. This would be particularly important in high accuracy applications when each module has a unique "personality profile".

Solution 2 - Modulate the sensor in the "linear" range only, its definition being when:

$$\text{Sin M} \approx \text{M} \qquad \text{Equation 15}$$

An equation for the above relationship can be derived from the Taylor Identity:

$$\text{Sin M} = \frac{M}{1!} - \frac{M^3}{3!} + \frac{M^5}{5!} \cdots \qquad \text{Equation 16}$$

Note that the fifth order and higher add less than 0.1% to the result, even at large angles, so they can be left out.

Then using the following for percent error the sensor must maintain at the required dynamic range:

$$\gamma = |\Delta\%| = \text{percent error}$$

if $\Gamma = 2\theta = x$ then:

$$\gamma = \left[\frac{x - \sin x}{\sin x}\right]100 = \left[\frac{x - \left(x - \frac{x^3}{6}\right)}{\left(x - \frac{x^3}{6}\right)}\right]100$$

and then:

$$x = \Gamma = 2\theta = \left(\frac{6\gamma}{100 + \gamma}\right)^{\frac{1}{2}} \qquad \text{Equation 17}$$

From **Equation 17**, you must design the sensor so that for the accuracy required (see **Figure 1**), "Γ", or "2θ" must not exceed (based on **Equations 13** and **14**) 0.08 radians to be within 0.1% uncertianty.

In other words, if the sensor designer is careful not to allow modulation beyond that value given by the above equation (Graphed in **Figure 26**) then the following equations can be used for simplification:

$$P_{p,s} = \frac{P_{in}}{2}[1 \pm \sin\Gamma] \approx \frac{P_{in}}{2}[1 \pm \Gamma]$$

for the Pockels Effect

and:

$$P_{p,s} = \frac{P_{in}}{2}[1 \pm \sin 2\theta] \approx \frac{P_{in}}{2}[1 \pm 2\theta]$$

for the Faraday Effect

Equations 18 and 19

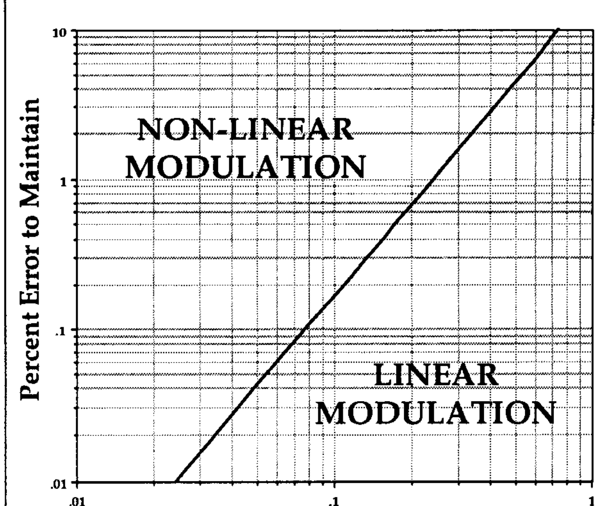


Figure 26 - Graph Showing the Maximum Modulation Possible to Declare "Linear Modulation"

Solution 3 - If the previous method fails to provide the dynamic range necessary for a linear sensor design, there is another way to enhance the result. Again taking a Taylor identity, this time for the arcsine of the modulation "sin M":

if:

$$P_{p,s} = \frac{P_{in}}{2}[1 \pm \sin M]$$

and:

$$\sin M = \mp\left[\frac{2P_{p,s}}{P_{in}} + 1\right]$$

then:

$$\arcsin(\sin M) = \sin M + \frac{(\sin M)^3}{6} + \frac{3(\sin M)^5}{40} + \frac{15(\sin M)^7}{336} \cdots$$

Equation 20

Note that the dynamic range for a particular accuracy needed gets better as the number of terms used increases.

- Another problem is that there will be a change in the value "P_{in}" in **Equations 13** and **14** due to optical attenuation, optical degradation etc. This necessitates adding a factor "α" describing the losses (mostly static losses but could account for low frequency dynamic losses as well)

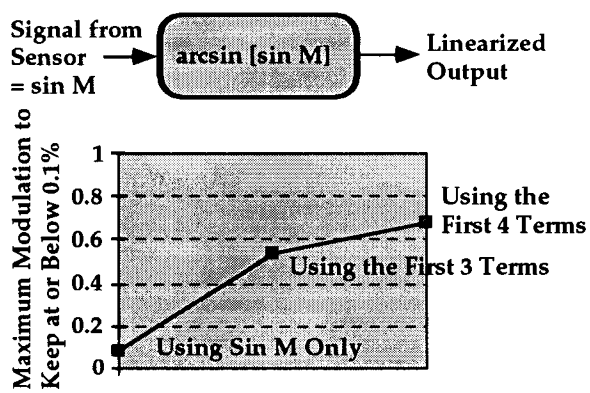


Figure 27 - One Method Used to Linearize an Optical Sensor

This relationship could be applied to the result either like the method in **Figure 27**, or if a digital computer is used, with pure math.

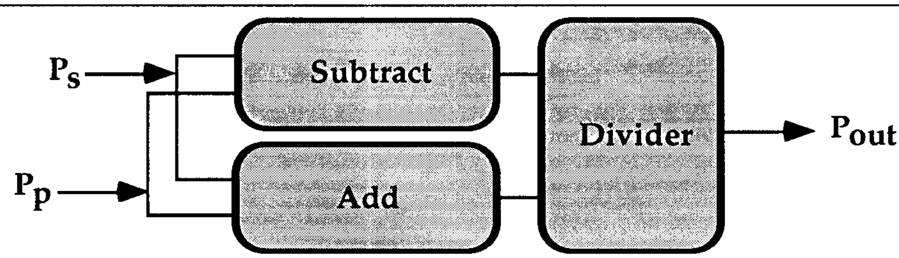
Many means exist to reduce this error, the two most popular are the "dc" and the "ac" methods both shown below:

The "dc" Method

If dc is to be measured and both analyzer fibers can be provided, then the circuit given in **Figure 28** is used.

The "ac" Method

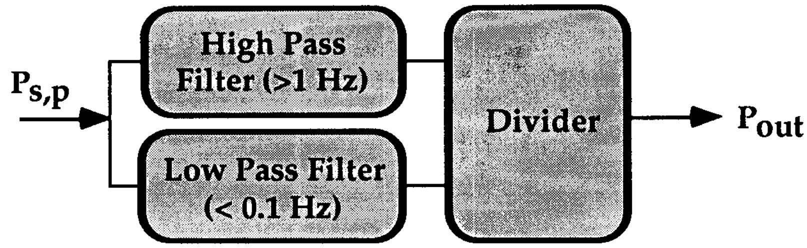
If dc measurement is not requird, then the method described in **Figure 29** is normally used. Its primary advantage is that only one down link fiber is required, thus sav-



$$P_{out} = \left\{\frac{\frac{\alpha P_{in}}{2}[1+\sin(M)] - \frac{\alpha P_{in}}{2}[1-\sin(M)]}{\frac{\alpha P_{in}}{2}[1+\sin(M)] + \frac{\alpha P_{in}}{2}[1-\sin(M)]}\right\} = \sin(M)$$

Equation 21

Figure 28 - The "dc" Method Used to Eliminate the Effects of a Varying Optical Input



$$P_{out} = \frac{\text{"ac" component}}{\text{"dc" component}} = \frac{\frac{\alpha P_{in}}{2}\sin(M)}{\frac{\alpha P_{in}}{2}} = \sin(M)$$ Equation 22

Figure 29 - The "ac" Method Used to Eliminate the Effects of a Varying Optical Input

ing costs (note that if this method is used, **Figures 13-15, 19 , 22, 23,** and **24** could all be redrawn so as to show one fiber down link). In addition the analyzer, normally a cube type, can then be a sheet type (providing only one orthogonal component) which is much less expensive.

In addition to the above means, servo methods and other mathematical means will also remove the effects from a varying light source. However, if the change is rapid, then none of the above will work as a new problem arises. If the either fiber up or down link(s) were perturbed differently (e.g.,a sharp bend - enough to cause mode coupling out of the core into the cladding). Then there will be two versions of "α", "α_p" and "α_s". One solution is to use "stiff" cable jackets or employ error analysis in the software. Such a method is given below in **Equation 23**:

- The crystal, waveplate and polarizers used in the optical circuit are sensitive to temperature. Much work was done to determine the severity of the problem and it has been determined that while some crystals have very low temperature coefficients, as do polarizers, the waveplates provide the greatest sensitivity. Some sort of temperature measurement using optical techniques (many exist) will allow for compensation within the analysis electronics. Again, for high accuracy systems, a "personality profile" of each sensor may be used for linearization given the temperature at the conductor.

- There are piezoelectric noises when step functions are applied to certain Pockels crystals. This problem can easily be solved by cutting the crystal's length so that the vibration mode is above the measurement range. In fault sensor designs where accu-

$$P_p = \frac{\alpha_p P_{in}}{2}[1+\sin(M)]$$

$$P_s = \frac{\alpha_s P_{in}}{2}[1-\sin(M)]$$

$$P_{out} = \left[\frac{P_p - \text{"ac" component only of } P_p}{\text{"ac" component only of } P_p}\right] - \left[\frac{P_s - \text{"ac" component only of } P_s}{\text{"ac" component only of } P_s}\right] = 2\sin(M)$$

Equation 23

racy is not important, but sensitivity is, this "problem" can be a "feature".

- There is a definitive noise component in the photodetection circuit. On the surface a potential problem for metering applications, but since the photodetection noise is more or less Gaussian, it will factor out in the integration process (when the waveforms have been converted to rms values and integrated over several seconds or minutes).

In conclusion there are solutions to most of the known problems. The major problems will be in keeping the field under measurement "clean" and homogeneous.

Industry Activity and Where are the Sensors?

At present there are many companies worldwide actively involved with the design of optical current and voltage sensors specifically related to the power industry. Even though the real need is for the distribution side of the industry, most of the effort has been directed to the transmission side as the monies have been more available.

What are some of the reasons why there is not widespread use of optical voltage and current sensors? Perhaps the major reason is that, since they are "low energy", they do not interface with existing meters and relays. Even though many manufacturers are designing and marketing digital systems now, there is still a need for a common set of guidelines to interface the low energy sensors to their products and there are several efforts to do so going on at present.

One other reason is that such new approaches need field testing to develop a confidence factor. And in the authors view, not nearly enough is being done, perhaps due to the depressed economy and the scarcity of funds to do evaluation. Along the same lines, existing specifications concerning component lifetime, loading and tolerances as well as the interface issue, compound the problem of testing for confidence.

A very important problem to note, is that it is quite common for a manufacturer not to pursue a particular approach due the inability to "protect it" (e.g., patents). Some of the best solutions have been around for so long, that manufacturers are afraid to use them feeling to do so would enable others to copy it and take a share of the market. This is an interesting delimina because if "new technology will replace old technology" (as stated in the beginning of this primer) then we all (users and manufacturers) must have the wisdom to decide when and how to incorporate it.

References

For additional reading on this subject and to find out about what BPA has been doing in this area, the following are available from the library or from the author:

1. D.C. Erickson, "**The Generation, Transmission and Recombination of Synthetic Microsecond Timing within the BPA Network for Primary Use in Fault Locating and Phase Angle Functions**", BPA Report, December 1973.

2. J. Esztergalyos, D.C. Erickson and J.N. Andres, "**The Application of Synchronous Clocks for Power System Fault Location, Control and Protection**", Paper presented at the 1984 American Power Conference in Chicago and the Eleventh Annual Western Protective Relay Conference, Spokane, WA, October 23-25, 1984.

3. D.C. Erickson, "**Automatic Fault Location Using 'Microtime"** , BPA Report No. AFL-100-01, May 1982.

4. Although many BPA test reports exist, a paper treating the design is provided in: D.C. Erickson, "**High Precision Remote Controlled Analog Fiber Optic Instrumentation link**", BPA Report No. FO-000-HD-1.

5. D.C. Erickson and B.O. Jordan, "**Fiber Optics and DTMF Provide Isolation for HV Testing**", Transmission and Distribution, pp. 12-14, July 1982.

6. D.C. Erickson, "**Bypass Vacuum Switch Controller Project**", BPA Report, May 1988.

7. D.C. Erickson, "**BPA Experience with Passive and Active Optical Sensors**", Presented at the September 1987 Gaithersburg Workshop: The Role of Optical Sensors in Power Systems Voltage and Current Measurements.

8. M.C. Mulder, D.C. Erickson, and A.L. Courts, "**A Microprocessor Based Monitoring and Protection System for a Series Capacitor Non-linear By-Pass Resistor**", Published in the IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, pp. 1879-1885, Sept/Oct 1980 and also presented at the 1979 Western Protective Relay Conference in Spokane Washington.

9. D.C. Erickson, "**A Super Wide Bandwidth Fiber Optic Analog Measurement System**", BPA Report No. ERFG-86-20, May 1986.

10. G.A. Massey, D.C. Erickson, and R.A. Kadlec, "**Electromagnetic Field Components: Their Measurement Using Linear Electrooptic and Magnetooptic Effects**", Applied Optics, Vol.14, No. 11, pp. 2712-2719, November 1975.

11. G.A. Massey, D.C. Erickson, and J.C. Johnson, "**Laser Sensing of Electric and Magnetic Fields for Power Transmission Applications**", SPIE, Vol. 88 on Polarized Light, pp. 91-96, 1976.

12. D.C. Erickson, "**The Design of Passive Current Sensors Using Magneto-Optics**", BPA Report No. DOE/BP 196 MO.

13. D.C. Erickson, "**The Design of Passive Voltage Sensors Using Electro-Optics**", BPA Report No. DOE/BP 197 EO.

14. D.C. Erickson, "**The Design of Passive Current Sensors**", Paper Presented at the Joint PES Portland Section April 1983 Meeting.

15. Ryszard Malewski and D.C. Erickson, "**Measurement Applications (Part 1)**", Paper written to be a part of a Tutorial entitled "Fiber Optic Applications in Electrical Power Systems" , IEEE Document 84 EH0225-3-PWR, Presented at the Winter 1985 IEEE PES Meeting in New York.

16. D.C. Erickson, "**The Use of Fiber Optics for Communications, Measurement and Control Within High Voltage Substations**", Paper presented at the 1979 Summer IEEE PES Meeting in Vancouver, B.C., Canada. Published in the IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, pp. 1057-1063, May/June 1980.

17. D.C. Erickson, et al, "**Fiber Optic Applications in Electrical Substations**", Presented at the Winter 1983, IEEE PES Meeting in New York, IEEE Special Document No. 83 TH0104-0 PWR.

18. E. A. Ulmer, "**A High-Accuracy Optical Current Transducer for Electric Power Systems**", IEEE Transactions on Power Delivery, Vol.5, No. 2, April 1990, pp 892-98.

19. Optra Inc. "**Fiber Optic Current & Voltage Sensors for Distribution Systems**", EPRI Research No. RP2734-4 (soon to be published).

20. E. Nakamura, et.al., "**Development of Fault Section Detecting System for Gas Insulated Transmission Lines**", IEEE Transactions on Power Delivery, Vol. PWRD-1, No. 1, January 1986, 19-26.

21. T. Mitsui, et.al., "**Development of Fiber-Optic Voltage Sensors and Magnetic Field Sensors**", IEEE Transactions on Power Delivery, Vol.PWRD-1, No. 1, January 1987, pp. 87-93.

22. T.W. Cease, et.al., "**Optical Voltage and Current Sensor Used in a Revenue Metering System**", IEEE Transactions on Power Delivery, Vol. 6, No. 4, October 1991, pp. 1374-79.

23. T. Meyer, et.al., "**Application and Field Trial of a High Accuracy Optical Current Transducer for Electrical Power Systems**", Presented at the EPRI Conference on Optical Sensing in Utility Applications", San Francisco, CA, May 14-15, 1991.

24. T. Sawa, et.al., "**Development of Optical Instrument Transformers**", IEEE Transactions on Power Delivery, Vol.5, No. 2, April 1990, pp. 884-91.

25. M. Kanoi, et.al., "**Optical Voltage and Current Measuring System for Electric Power Systems**", IEEE Transactions on Power Delivery, Vol. PWRD-1 No. 1, January 1986, pp. 87-93.

26. Dingding Tang, A.H. Rose, G.W. Day and S.M. Etzel, "**Annealing of Linear Birefringence in Single-Mode Fiber Coils: Application to Optical Fiber Current Sensors**", Journal of Lightwave Technology, Vol. 9, No. 8, August 1991, pp. 1031-1037.

27. P. Meyruiex, et.al., "**A Great Step in the Industrialization of Optical Measuring Reducers**", CIGRE, paper 34-15, 1988 Session, August 23-September 3, pp. 1-10.

28. 3M Austin Center, Electrical Products Division, Preliminary information and personal discussions 1992.

29. A.N. Tobin, et.al., "**Application of an Optical Fibre Current Sensor to Electricity Supply Protection**", SPIE, Vol. 1169, Fiber Optic and Laser Sensors VII (1989), pp. 201-209.

30. O. Tønnesen, et.al., "**A New 132 kV SF6 Insulated Electrooptic Instrument Transformer**", Presented at the EPRI Conference on Optical Sensing in Utility Applications", San Francisco, CA, May 14-15, 1991.

31. Optical Technologies, Inc. "**Phase-Modulated Fiber-Optic Current Transformer/ Voltage Transformer**", EPRI Report No. EPRI EL-7421, Project 2734-3, July 1991.

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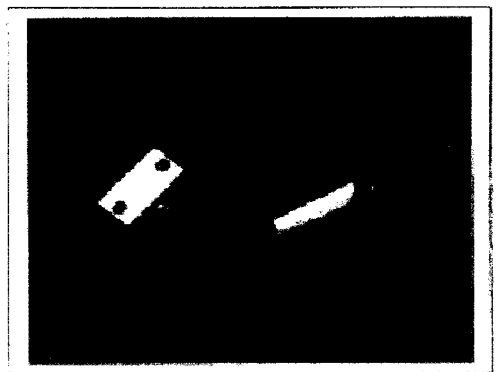
*ST is a trademark of AT&T



OPTICAL AND ELECTRICAL CHARACTERISTICS* AT MIN 150 mW ILLUMINATION

Characteristic	Symbol	Min Value	Typ. Value	Unit
Electrical power output	P_o	55	60	mW
Open circuit voltage	V_{oc}	6.5	6.6	V
Short circuit current	I_{sc}	10.5	11.2	mA
Voltage at max. power	V_m	5.8	5.9	V
Current at max. power	I_m	9.5	10	mA
DC Impedance at max. power	Z	610	590	Ω
Conversion efficiency	η	36	40	%
Modulation cut-off frequency	ν	10	10	MHz

*Active illumination area is 1.5 mm in diameter. Temperature = 25 °C

THERMAL CHARACTERISTICS	Symbol	Value	Unit
Voltage temperature coefficient	dV_{oc}/dT	-11.1	mV/°C
Wavelength temperature coefficient	$d\lambda/dT$	0.3	nm/°C

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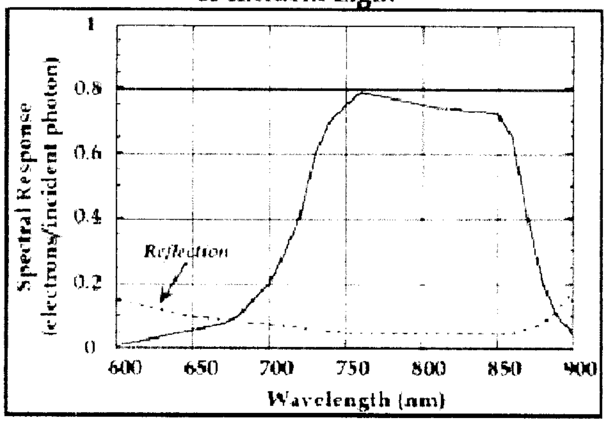
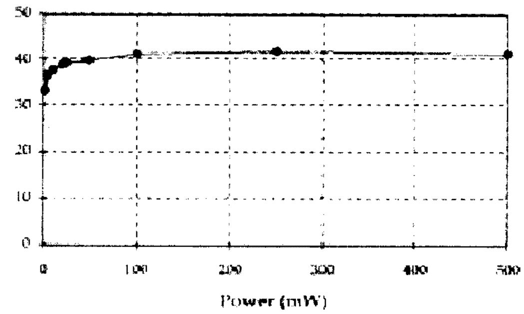
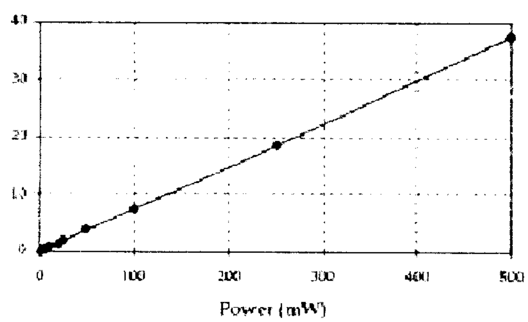
Spectral Response vs Wavelength of Incident Light



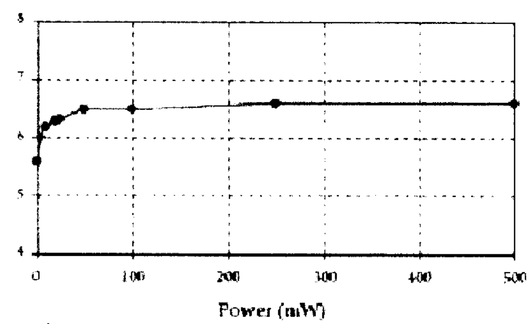
Efficiency vs Power



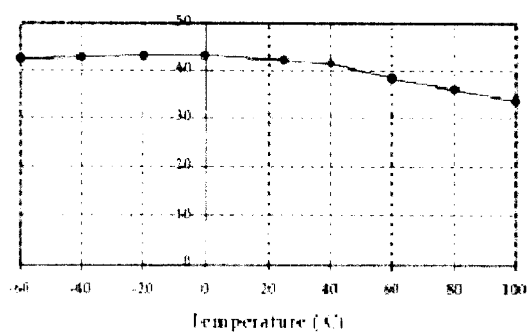
Isc vs Power



Voc vs Power



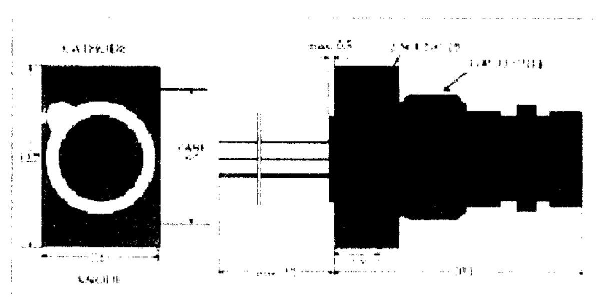
Efficiency vs Temperature (100 mW illumination)



PPC-6E-ST

Power converter packaged in an ST receptacle.

Drawings for the FC and SMA receptacles are available upon request. (All dimensions in mm)



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