NOVEL CURRENT AND VOLTAGE SENSORS FOR DIGITAL INSTRUMENTATION IN POWER STATIONS

Traian-Titi SERBAN, Elena DOICARU
University of Craiova
e-mail: tserban@elth.ucv.ro, tel: 40-251-435724 ext: 106

Abstract: This paper presents some special current transducers designed to work especially with digital measurement, monitoring and protection equipment. The main feature of the digital instrumentation is that it does not ask power transfer for information transmission. The inputs have nearly zero or very high impedances, so the burden is insignificant in most of the practical cases. In this situation, current and voltage transducers were designed based on new principles. This paper comes with an interesting offer for the high voltage power stations: the electro-optical transducers built in the last decade of the past century. Based on the electro-optical effects related to the magnetic and the electric fields, the novel transducers have multiple advantages regarding the precision, the bandwidth and the security of the instrumentation and the human operators. Having an intrinsic maximum level of insulation, these transducers are more reliable and ask for minimum maintenance.

Keywords: Fiber optic, Faraday Effect, Pockels Effect, Electro-optical Current and Voltage Transducers

INTRODUCTION

The classical way for picking the current and voltage signals from the power systems involve heavy electromagnetic current and voltage transformers (CVT). Their narrow bandwidth, limited overload and strong distortions associated with the saturation and hysteresis effects of the classic CVT are very prohibitive features when they are put to work with modern digital equipment. The first device that replaced the current transformers was the Rogowski coil based current transducer (RCBCT). In 1992, Power Electronic Measurements (PEM) from Nottingham brought back on the market the RCBCT. Two different categories of industrial applications are using it: the monitoring measurement, where low frequency currents are to be estimated in steady-state with the best accuracy the transducer can get, and the transient wide-range overload and short-circuit current measurement for the protective goals. The last case is well studied since the first applications of the coil were in the quantic-physics experiments to estimate the high-frequency magnetic fields and currents.

In the low frequency range there are fewer designs and descriptions. Using the RCBCT at the main industrial frequency (50/60Hz) is new since the replacement of the current transformers was not considered until now.

Conventional means of measuring high voltages and currents rely on the measurement consuming a small amount of power from the system. The new sensors are based on the changes in the properties of some special materials when electrical or magnetic fields are applied to them. Such kinds of effects were never used before because of the lack of the electronic devices and technology. The measuring equipment itself provides the power required for making the measurement. These measurement techniques rely on various mechanisms by which a material rotates the polarization of light passing through when electrical and/or magnetic fields are applied to them: the Kerr effect, the Pockels effect, and the Faraday effect. The amount of rotation depends on the electric or magnetic field. The performance is determined largely by how well one can measure the change in polarization of the light. High quality polarizing film has a transmission ratio of 1000:1 between aligned and crossed.

For the current sensors, the Faraday effect (1845) is applied. It involves a laser beam passed through a special optic material that changes its optical properties, resulting in the rotation of the polarising plan.

The high voltage measurement uses the Pockels effect: the linear change in the birefringence of a special crystal when exposed to an electric field. The voltage information is derived from the optical changes and the dimensions of the crystal, since the transducer measures the electric field directly. For lower voltages, Kerr cells are more appropriate since their change in the birefringence is proportional to the square of the applied electric field.

Both types of CVT provide the best insulation properties, since they are active devices with no electrical conductive properties. The sensors may have a digital output making them directly compatible with the modern instrumentation for measurement, monitoring and protection (MMPI).

THEORETICAL BACKGROUND

The optical effects of the electromagnetic field were discovered in the nineteenth century, but they were used as a theoretical base for the current and voltage transducers only in the last decades. These effects stay mainly in modifications of the optical properties of some transparent materials when an external electric or magnetic field is applied to them. The most common effects that are used to build current and voltage transducers happen in the polarisation of the light passing through the said optical medium: the rotation of the polarisation plan or the birefringence of the medium.

The Faraday Effect

A plane-polarized wave can be decomposed into two circularly polarized waves. The rotation of the plane of polarization of light as it propagates through the optical piece in a direction parallel to an applied magnetic field is called the Faraday effect, or Faraday rotation. The rotation due to a magnetic field may be expressed in terms of e/m, the ratio of the charge of an electron to its mass. According to the theory of Lorentz, an electron moving in its orbit about an atomic nucleus will change its frequency of revolution which in turn leads to a rotation of the plane of polarized light through the affected object. This angle of rotation a of the circularly polarised light has been shown to be proportional to the strength of the magnetic field and the distance the light must pass through the medium:

$$\alpha = \frac{e}{2mc^2} \lambda H \frac{dn}{d\lambda} = VHl \qquad (1)$$

where e is the charge of the electron, m is the mass of the electron, c is the speed of light, λ is the wavelength of light, H is the magnetic field strength, $dn/d\lambda$ is the derivative of the index of refraction with respect to the wavelength, and V is the Verdet constant.
A simplified illustration of the Faraday effect is shown in figure 1.

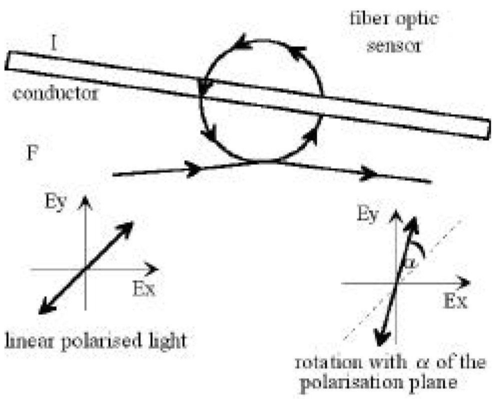

Fig 2. The Faraday Effect

The accepted values for the Verdet constant (Jason 1997) are shown in table T1.

Table T1. Verdet constant for few usual materials

Material	*Verdet constant (°/T m)*
Light Flint	533.33
Heavy Flint	1016.66
Very Heavy Flint	1483.33
Jena Glass (Barium)	366.66
Phosphate	266.66

The principle of the current electro-optic sensor is shown in figure 3. A LASER beam, produced by an electronically driven light source, is passed through a polarising element. The circularly polarised light is kept on a parallel direction with the magnetic field around the current carrying conductor, by mean of an optic fibre that is, in fact the electro-optic sensor.

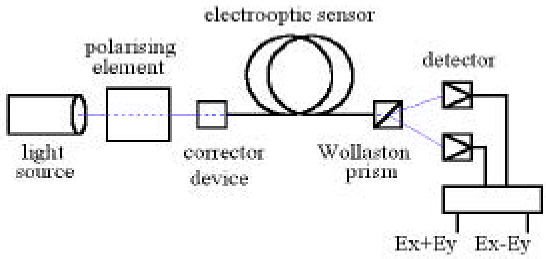

Figure 2. Faraday Effect - Based Electro-optic Sensor

The optical properties of the fibre are those that change when magnetic field is applied. In fact, the sensor is one for magnetic field and is used as a current sensor based on the linear dependence betwee the current and the magnetic field around it. A Wollaston prism splits the light beam with a rotated polarisation plan into two unequal beams with the information of orthogonal components of the polarisation direction. Two detectors extract the information about the rotation of the polarising plan and generate the Ex, Ey voltages proportional to the components of the polarising direction. Finally, the rotation angle and the amount of the measured current is computed inside the measuring instrument.

The Pockels Effect

The Pockels effect is the dependence of the linear birefringence of some materials on the applied electric field. The linear birefringence of a medium is the phenomena whereby two orthogonal linear directions of light polarization travel at different velocities.

The direction of the applied electrical field and that of the light beam can be parallel or orthogonal one each other, generating longitudinal and transversal Pockels effect respectively. Substances such as KDP (Potassium Dihydrogen Phosphate), KD*P (Deuterated KDP) and LiNbO3 (Lithium Niobate) show large Pockels effects and are very popular as electro-optic modulators for laser work. $Bi_4(GeO_4)_3$ (Bismuth Germanate) with a cubic crystal structure can be used as medium of the light propagation, as it exhibits an important transversal Pockels effect, which varies the refractive index proportionally to the electrical field (Rutgers 1990).
A light beam is modulated in accordance to the pulsed voltage signal at the input of the divider, in order to produce a rotating *elliptical polarization*. When the polarized light is passed through the Pockels cell with an electrical field distribution, the light has phase delay. By detecting the intensity of the light through an analyzer, the electric field can be calculated. The induced phase delay δ, between two orthogonal light components is given by formula (Santos 1997):

$$\delta = 2 \pi \Delta n L / \lambda \qquad (2)$$

where λ is the wavelength of the light, *Dn* is the induced birefringence and *L* is the length of the crystal. The induced birefringence can be computed through the next formula (Rutgers 1990):

$$\Delta n = n_o^3 \cdot k_P \cdot E \tag{3}$$

where n_o is the refractive index in the absence of the electric field, k_P is the Pockels coefficient of the electro-optical material, and E is the intensity of the electric field.

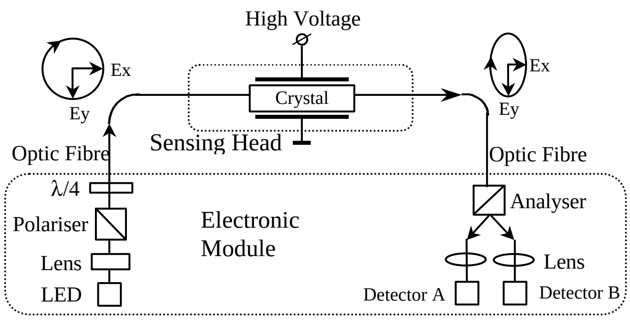

Figure 3. Principle of the Pockels Cell Voltage Sensor

If two detectors, A and B, are used to analyze the light in the long (Ey) and short (Ex) directions of the output polarization ellipse (Rutgers 1990), then:

$$\frac{Ey - Ex}{Ey + Ex} = \sin\left(\frac{E}{E_0}\right) \tag{4}$$

where E_0 is the field strength leading to a phase shift of $l / 4$ (usual value is E_0 = 5…30 kV/cm for the most common electro-optic materials).

The sensors are electric field sensors. The relation between the applied voltage and the electric field is used to derive the voltage, depending on the geometric dimensions electro-optic crystal. In order to use the Pockels cell as voltage sensors one must calibrate each device individually.

The entire voltage can be applied across the electro-optical crystal, but a capacitive divider can always be used in order to apply only a fraction of the voltage to be measured. The crystals have a lower voltage stress but the most important is that the side effects (such as piezoelectric effect) are diminished at low voltages.

PRACTICAL IMPLEMENTATIONS

The Canadian Corporation NXTPhase builds high-voltage electro-optical current sensors with the configuration shown in figure 4.

The sensor has two main components (NXTPhase 2003): the measurement sensing head and the control electronic module. The sensing head includes a circular polariser (λ/4 waveplate) and an optic fibre disposed in one or more turns around the current carrying conductor. The free head of the fibre is optical coupled to a mirror that turns back the light with rotated polarising plan, through the optic fibre to the electronic module.

The electronic module includes a light source that sends pulsed light beam through a wave guide to a linear polariser, then to a polarization splitter (creating two linearly polarized light waves), and finally to an optical phase modulator. The beam is sent to an optical fiber in the sensor head through a quarter-wave plate that creates right and left hand circularly polarized light from the two linearly polarized light waves. The two light waves traverse the fiber sensing loop around the conductor, reflect off a mirror at the end of the fiber loop, and return along the same path. While encircling the conductor, the magnetic field induced by the current flowing in the conductor creates a differential optical phase shift between the two light waves due to the Faraday effect. The two optical waves travel back through the optical circuit and are finally routed to the optical detector where the electronics de-modulate the light waves to determine the phase shift. The phase shift between the two light waves is proportional to current. An analog or digital signal representing the current is provided by the electronics to the end user.

The standardisation of the current and voltage electro-optical sensors is a developing process, done by the IEEE Working Groups (Serban 2003), so the manufacturers integrated already new sensors in the digital equipment. The trend in the field is to integrate all sensors in monolithic measuring devices (Brojboiu 2003), so the both described electro-optical effects are now used together to build common sensors for current and voltage (figure 5). The current and voltage sensors are driven by the same source of coherent light (LASER), split by a Wollaston prism. The two outputs give the current and voltage signals.

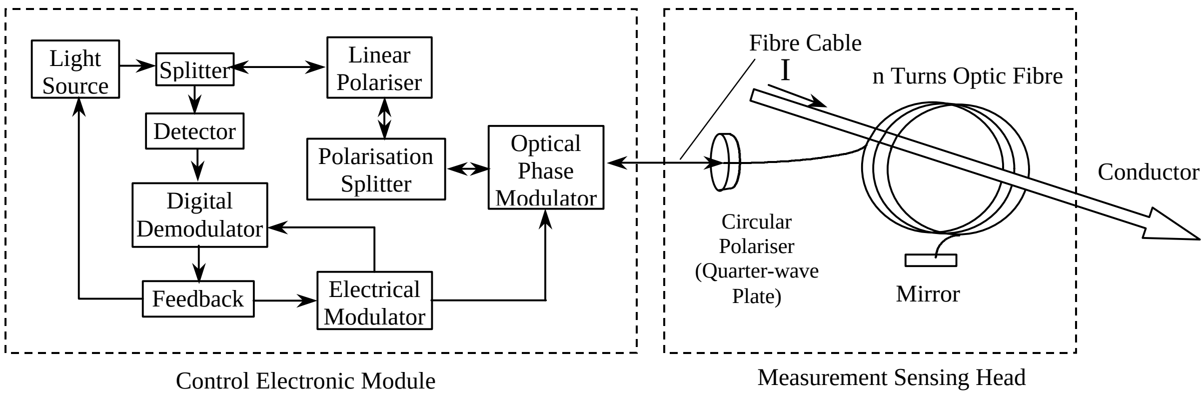

Figure 4. NXTPhase Model for High Voltage Electro-optical Current Sensor

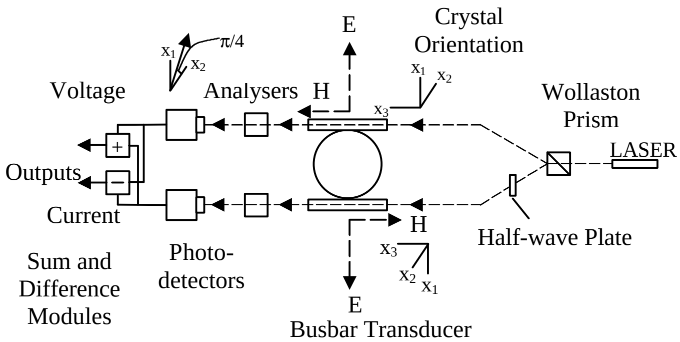

Figure 5. Schematic of the Current and Voltage Electro-optical Transducer

INTEGRATED MONITORING AND PROTECTION SYSTEMS

The power systems are designed by systems integrators as completely integrated complex systems with centralised MMPI. The interface between the current sensors and the MMPI is usually achieved by the "Instrumental Transducers" functioning as analog signal adders (Σ). Figure 6 presents the most common configuration for measuring the primary features in a power system with MMPI. Three independent channels are dedicated to the line currents. Each current sensor (CS1…CS3) is included in the same time in the monitoring section and the protection section of the MMPI. The old rule of thumb that says that the monitoring and the protective sections will never share the same transducers is no longer valid, since the electro-optical sensors are much reliable than ever before. One current channel is assigned to the homopolar current for grounded short-circuits' detection. Seven voltage channels are dedicated to the phase voltages (3), to the line voltages (3) and to the homopolar voltage (1).
The instrumental transducer is a complex circuit with a generic adding function that allows to conventional transducers to be used along with the new optical sensors. This function includes special functions that can be configured separately on every channel. The adder is a multifunctional device built around a performant analog multiplexer that offers to the outputs of the sensors a selective access to the digital system.

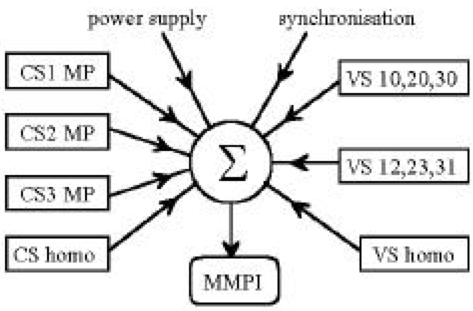

Figure 6. Configuration for a MMPI Connection in a High Voltage Power System

The instrumental transducers may be interconnected on dedicated buses for data communications. Current and voltage levels, waveforms and synthetic values of the measured features may be transmitted over the data buses. Communication and data buses are gathered together in so called process buses, which are a part of the integrated MMPI in the power system (figure 7).

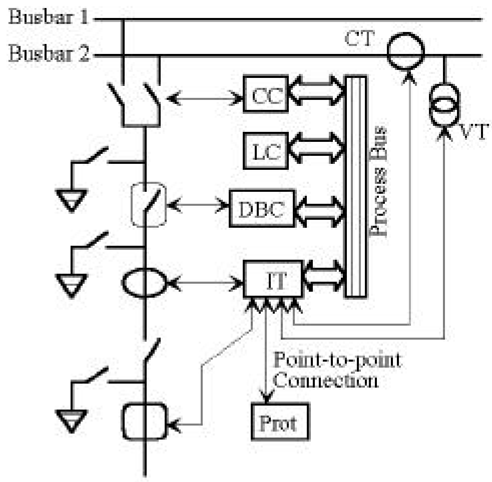

Figure 7. Instrumental Transducers' Connection

Local Controller (LC) identifies the location of the breakers' controllers searching on the process bus and the commutation controller (CC). The local processing device transmits the selection command for the appropriate measuring transformer, every voltage transformer being connected to its IT.
The breaker tripping decision is taken in the Digital Breaker Controller (DBC), following a complex information transfer in point-to-point mode, next a waveform analysis and finally the verification of many inter-conditionings.
Special electronic modules supplied by different producers integrate the electro-optical CVT in the monitoring systems. ALSTOM put on the market different types of electro-optical current and voltage stand-alone transducers, offering modular rack-mounting platforms (CVCOM-300) that synchronise the signals from the sensors on the three phases of the high voltage power systems, offering many solutions for connecting electro-optical CVT in the power stations.

Figure 8 presents one of the possible configurations.

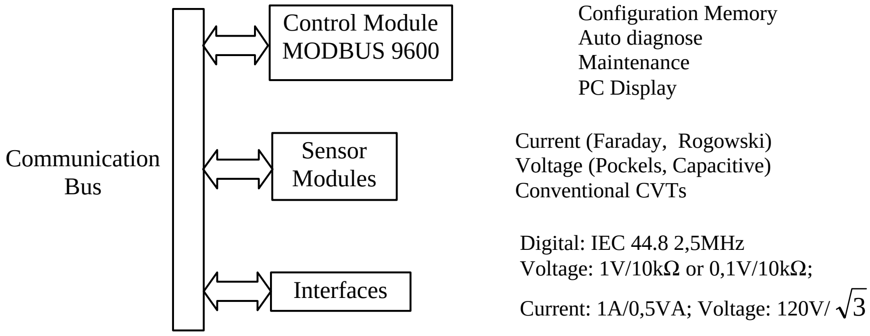

Figure 8. CVCOM 300 Rack

CONCLUSIONS

The new MMPI for the high voltage stations has better performances regarding the input stages and functionality. As they do not need any power transfer from the power system, the associated CVTs may have the main features focused on the precision, speed and isolations performances.

There are two main directions in the replacement of the old current and voltage transformers. For low and medium voltage systems, characterised by high short-circuit currents, Rogowski coil seems to be the most appropriate current transducer, as it has the best performance in the range of the very high currents. For the medium voltage measurements, one can use Kerr cells, as their sensibility is higher than Pockels cells'.

For high voltage systems, the optical current transducers based on the Faraday effect and the optical voltage transducers based on the Pockels effect are the best choice, as they exhibit the best isolation and reliability performances. Both types of current transducers are suitable for their conjunction with digital data acquisition systems, as they can be designed with digital data transmission.

The first exponents of the new generation of CVT have already been put on the market (NXTPhase 2003). CEI and IEEE Working Groups are focused on the standardisation, having already elaborated international rules for the interchangeability and the compatibility of all new sensors (Gross 2000).

In all new designs of high voltage stations and substations, the new CVT are a real option that must be considered.

REFERENCES

Brojboiu M, Serban T-T, Leoveanu M.S. "*Concerning the Implementation of the Electro-optical Sensors for Voltage Measurement in Distribution Stations*", Proceedings of Power Systems Conference, Timisoara, 2003;

Jason D. Darfus, "*The Faraday Effect*", Physics Department, The College of Wooster, Wooster, Ohio 44691, May 1, 1997;

Gross R., Herrmann H-J, Katschinski U, and others: "*Substation Control and Protection Systems for Novel Sensors*", Cigre, Session 2000, 12/23/34-03;

Rutgers, W R, Kleijne M, Coreman C G A , Van der Wey A H , "*Fiber-optic Current and Voltage Sensors for Application in High Voltage Systems*", Kema Scientific & Technical Reports 8 (6), 1990;

Santos J C, Taplamacioglu M C, Hidaka K, "*Optical High Voltage Sensors Using Pockels Fiber Crystals*", 10-th International Symposium on High Voltage Engineering, Montreal, Canada, August 25–29, 1997;

Serban T-T, Brojboiu M, "*Trends and Perspectives in the Development of a New Generation of Current Sensors for High Voltage Stations*", Proceedings of Power Systems Conference, Timisoara, 2003;

NXTPhase, "*NxtPhase Technical Specifications, NXCT Optical Current Sensor*", 2003, www.nxtphase.com;