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ELECTROOPTIC METHODS FOR MEASUREMENT OF SMALL DC CURRENTS AT HIGH VOLTAGE LEVEL

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Abstract

Two electrooptic methods for measurement of DC currents at high voltage levels, extending from the nA range and up to the milliamperes range have been developed. First, by switching the polarity of a measured DC voltage across a Pockels cell, DC currents can be measured and transmitted along an optical fibre to an electrooptic converter. Second, by use of an electronic circuit the measured signal can be converted into a modulated frequency form for transmission along an optical fibre. These systems are described, measurement results are presented and improvements to be made in the future are outlined. The measuring methods can be used both for development and supervision of electrical insulating systems.

Introduction

Measurements of small DC currents at high voltage levels extending from the nA range and about six decades up to the milliampere range are of considerable interest both for development and supervision of electrical insulating systems. Leakage currents on for example outdoor insulators have been studied for many years [1] as they can yield valuable information about the flashover characteristics of the insulation systems. The increasing use of HVDC transmission systems has greatly emphasized the requirement of a deeper understanding of the behaviour in DC insulating systems. The development of electrooptic methods for the measurement of small DC-currents at high voltage levels has opened new ways for research in this area.

For this purpose, two different optical current transducer principles have been developed as presented in the following sections. One transducer contains a Pockels cell which modifies the light in a crystal according to the measured current or voltage. An analog signal is transmitted along an optical fibre to an electrooptic converter. The other transducer contains an electronic circuit for converting the current or voltage into modulated frequency form for transmission along an optical fibre.

DC voltage and current measurement using the Pockels Effect

Pockels devices and their uses in the measurement of AC voltages have been described extensively, [2]-[7], with the Pockels cell used being described in [7]. The Pockels cell used here is based on the electrooptic effect which occurs when an electrical field is applied to a Bi$_2$SiO$_5$ crystal.

The principle of the cell is shown in fig. 1.

![Fig. 1: Arrangement of the optical system.](image)

Light of wavelength 0.85 μm from a high-radiance LED is launched into a step-index multimode glass fibre (100 μm core). At the cell the light passes through a polarizer and a ½ plate and thus becomes circularly polarized. Dependent on the voltage applied to the Bi$_2$SiO$_5$ crystal, this circularly polarized light then is changed to elliptically polarized light due to the birefringence of the crystal. This phase modulation is finally converted to amplitude modulated light by an analyser. The modulated light is then send back to an electrooptic converter via a second fibre. The light detector is a PIN photo diode.

The principle of the amplitude modulation is shown in fig. 2.

![Fig. 2. Amplitude modulation principle: Optical power transmission versus input voltage. Also shown is the applied AC voltage versus the modulated optical power output.](image)
If an AC voltage is applied to the cell, the output light power will consist of an AC component overlaid on a DC component as shown in fig. 2.

The AC/DC ratio $m$ is given [10] by

$$ m = \frac{\nu(t)}{\nu} = \frac{f(V(t))}{V(t)} $$

where

$$ f(V(t)) = \frac{\sin [(\nu(t) - 2\theta d)^2 + 2(\nu - d)^2]^{1/2}}{(\nu(t) - 2\theta d)^2 + 2(\nu - d)^2]^{1/2}} $$

$V(t)$ the input voltage signal, $V_\nu$ the half wave voltage, $\theta = 10.5^\circ/mm$ is the optical activity of the crystal for light of optical frequency, $d$ and $d'$ the thickness of the crystal (approx. 5 mm).

The cell is designed for long time exposure of voltages up to 500 Vrms, and for voltages in this range $f(V(t))$ varies between 0.5738 and 0.5673 i.e. $f(V(t)) = c$ is a constant.

Thus, the modulation ratio $m$ varies linearly with the input voltage signal $V(t)$, i.e. a sine voltage applied to the cell will yield an analog light power output with a sine component overlaid on a DC component.

The block diagram for the measuring system is shown in fig. 3. The circuit compensates for the optical losses which occur in the optical fibres connecting to the sensors, by means of a negative feedback loop.

For DC measurements we have developed a system which is shown in fig. 2. The circuit compensates for the optical losses which occur in the optical fibres connecting to the sensors, by means of a negative feedback loop.

1. Clearly, although polarization modulation is the mechanism whereby Pockels sensors function, it is an amplitude modulation which is actually observed and the sensors will be sensitive to the optical power losses rather than the voltage induced intensity modulation in the Pockels cell. Therefore, some form of intensity referencing is required for stable long term sensor operation. There is no problem when measuring. AC signals as the DC level in the detected light signal can be used as a reference but this could not be done if a DC voltage was applied directly to the Pockels cell as the reference and signal would not be separable.

2. Furthermore, the response of the Pockels cell to a step voltage is not, as expected from Figure 1, a step change in transmission. There is an initial jump (or fall) in transmission proportional to the height of the step voltage but this is followed by a decay towards the initial transmission which has a time constant of about one second. This effect is thought to be due to polarizations, which change the optical power of the BSO crystal, being induced by a "long term" DC field. A clear consequence is that transmission through the Pockels cell will not be a stable measure of a DC voltage applied across the cell.

The switching circuit Figure 4 is based around two high voltage transistors $T_A$, $T_B$, with the Pockels cell electrodes being each connected to one of the transistor collectors. The transistor collectors are connected via resistors $R_A$ and $R_B$ to the positive side of the voltage to be measured and the emitters to the negative side. The currents flowing into the bases of the transistors are independently controlled by the light levels following on the two photodiodes $PD_A$, $PD_B$. The resistors $R_A$ and $R_B$ are relatively large ranging from 1 to 10 M$\Omega$ but the impedance of the Pockels cell is much larger (hundreds of M$\Omega$) so that the voltages at the Pockels cell electrodes can be controlled independently by varying the light levels on the photodiodes. The switching operation of the circuit can be explained by looking at the voltage across the Pockels cell when one photodiode $PD_A$ is in darkness and the other $PD_B$ is illuminated with say 300 $\mu$W, with the voltage to be measured being 300 V. The current flowing into the base of transistor $A$ will only be the dark photodiode current of the order of 10 nA and the transistor will not conduct significantly. The voltage at electrode $A$ of the Pockels cell will therefore be effectively 300 V. The current flowing into the base of transistor $B$ will be the order of 150 $\mu$A (photodiode sensitivity is 0.5 $\mu$A/W). With a transistor current gain of 5 and load resistor $R_2$ of 1 Megaohm, this current is easily enough to switch the transistor producing a voltage across electrode $B$ of the Pockels cell within a few hundred milliseconds of the negative side of the DC voltage to be measured. Therefore in this case there will be a voltage induced across the Pockels cell with a magnitude within a few hundred millivolts of the voltage to be measured, electrode $A$ being positive with respect to electrode $B$. Clearly if the situation is reversed and $PD_B$ is illuminated while $PD_A$ is not then the polarity of the voltage across the Pockels cell will also be reversed.

In the system block diagram Figure 5 it can be seen that the photodiodes are illuminated by light carried from two Light Emitting Diodes on ground potential via two separate optical fibres. The LEDs are square wave current modulated so as to be periodically switched on and off and are in mutual antiphase i.e. while one LED is emitting the other is not. The fibre used is relatively large having a core diameter of 600 microns, so that using standard LEDs 300 microwatts or more can easily be transmitted to the photodiodes.
will be assessed with reference to the results of a preliminary test, shown in Figure 6. Measuring AC voltages. Unmodulated light is launched as the applied voltage was varied between 0 and 300 V. The modulated light is carried by a second optical fibre to a receiver at ground level.

System performance - Range, Linearity, Resolution.

In this section the potential system performance will be assessed with reference to the results of a preliminary test, shown in Figure 6. The graph shows the amplitude of the sensor output square wave (read from an oscilloscope) versus the DC voltage applied across the sensor (read from a high accuracy digital voltmeter) as the applied voltage was varied between 400 mV and 300 V.

Fig. 6: Amplitude of receiver output square wave versus DC voltage applied across the sensor.

The most noticeable feature of the graph is that from the maximum applied voltage down to about 1 V it is linear with slight nonlinearity being observed in the range from 1 V to 400 mV. This nonlinearity is due to the emitter-collector voltages becoming comparable to the applied voltage. Also in this region noise becomes significant (receiver shot and Johnson noise combined are about 3 mV RMS) so the lower limit on the voltage that can be measured is about 0.5 V. At the upper end of the range results were only taken up to an applied voltage of 300 V as this was the withstand limit of the transistors used. Transistors are available which will withstand 1 kV or more and thus the measurement range can easily be extended up to 500 V, which is within the maximum level of the Pockels cell.

The sensor can measure currents if connected across a resistor through which they flow. For linear operation the series resistance should probably be an order of magnitude less than the resistors RA, RB. The minimum measurable current would be that which produces a 0.5 V drop across RS and if for example RS was 100 kΩ (RA = RB = 1 MΩ) the minimum measurable current would be 5 μA. If smaller currents were to be measured RA, RB would have to be increased. Raising resistors RA and RB will have two effects - firstly the switching time will be increased as this is determined by RA, RB and the capacitances of the photodiodes PD1, PD2. This will lead to an output which is not a proper square wave, but as an exact square wave is not essential to operation (we are only interested in transmission changes when the polarity is inverted) this effect would not cause the lower limit for current measurement. If RA and RB are raised to about 10 MΩ then there will be a voltage drop across them of about 0.5 V due to the photodiode "dark currents". This sets the upper limit of RA, RB at about 10 MΩ and hence the upper limit for RS at about 1 MΩ. This in turn sets the lower limit for the current to be measured at around 0.5 μA.

Current to frequency transducer

An alternative current measuring device using a unijunction transistor has been developed and tested. A unijunction transistor, UJT, is a three terminal device, constructed as a n-type silicon resistor with ohmic contacts at both ends. An emitter rectifier contact E is placed between the two ohmic contacts, here called B1 and B2. Under normal operation, VB, the voltage of B2 relative to B1, is positive. Now, when a voltage equal to n · VB relative to B1 is applied to the emitter E, a current will start to flow. The factor n will typically be in the range 0.50-0.75. Once the current starts to flow an avalanche process turns the E-B1 region into a highly conducting path with a negative resistance characteristic. Therefore, a current pulse train with a frequency dependent upon the applied voltage, is established. The UJT component has a very stable trigger voltage and good temperature stability.

The diagram of the current transducer is shown in Figure 7.

Fig. 7: Current to frequency transducer. UJT: Unit junction transistor, C: Discharging capacitor, Ic: Current to be measured.

The voltage at which the capacitor will be discharged is proportional to the auxiliary supply voltage to the UJT, and thus, the stability of the supply voltage will determine the accuracy of the current measurement. The capacitor discharge currents are passed through a LED and the light pulses (approx. 1 μsec. duration) are
transmitted via an optical fibre to a receiver, where
the pulses are counted.

The calibration curve for the transducer in Figure
7 is shown in Figure 8. The pulse frequency versus the
DC current is linear within the accuracy (±1%) of the
measuring instruments used.

![Fig. 8: Calibration curve for the current transducer. Pulse frequency versus measured DC current.](image)

For example, at a current level of 1 mA, the pulse
frequency is approximately $10^4$ pulses per second, and a
resolution of ±1% is obtained within $10^{-2}$ seconds. However, at 10 µA level a measuring time of 1 second is
necessary to obtain the same resolution.

Instead of just counting the discharge pulses, they
can be used as timing pulses for a high frequency coun-
ter operating at e.g., 10 Megacycles per second, and thus
the number of counts are inversely proportional to the
measured current. In Figure 9 a modified circuit for
measuring higher DC current levels is presented.

![Fig. 9: Modified current to frequency transducer, without auxiliary power supply; the bypass current through transistor 1 is passed through a parallel Zener diode voltage regulator.](image)

The bypass current through transistor No 1 is led
through a parallel voltage regulator (e.g., a Zener
diode), which supplies the voltage to the UJT. The lower
limit of the current that now can be measured is deter-
mined by the minimum current needed to activate the
UJT. The ratio between the current bypassed by tran-
sistor No 1 and the corresponding current through tran-
sistor No 2 (which charges the capacitor) will very
closely be equal to the inverse ratio of the emitter
resistances $R_3$ and $R_4$. However, the transducer circuit
in Figure 7 does not have the same wide dynamic range
as the circuit in Figure 5, as the base emitter voltages of
the two transistors will not be complete when the transistor currents are of different
magnitude.

Discussion and conclusions.

For long term operation inclusion of a battery in
either of the measurement methods described here is not
desirable.

With the Pockels device system there is a require-
ment for the power supply to generate only about 100 µA
and enough voltage to reverse bias the photodiodes (a
few Volts), so the power requirement is less than 0.5 mW.
This could be generated by sending optical power up to
the high voltage level or if the current to be measured was
larger then a few milliamperes some would be drawn
off to power a Zener diode. Systems are now under devel-
opment in which the polarity inversion would be per-
formed by a bridge arrangement of optoelectronic com-
ponents (e.g., high voltage photodiodes) and which would
not require an auxiliary power supply.

During the preliminary test the polarity inversion
was at a frequency of 250 Hz and the signal to noise
ratio for 300 V DC input was greater than 60 dB. In a
measurement situation the output square wave would prob-
bly be rectified and low pass filtered to give a DC
output. If the desired system response was, 10 Hz then a
signal to noise ratio of 70 dB would be achievable.

Regarding the current to frequency transducer the
current range which can be measured by the circuit in
Figure 5 extends over about four orders of magnitude.
The lower current limit is determined by the emitter
current of the order 0.1 µA, required to bring the UJT
into the negative resistance region.

However, by applying short negative voltage pulses
of approx. 0.75 V (generated by a second unijunction rel-
axation oscillator) to the base $B_2$, the lower current
limit can be reduced to about 1 nA. The upper limit of
the measured current is about 1 mA at which the emitter
E to base $B_1$ resistance changes from the negative to
the positive region.

In conclusion we can say that two alternative transducer
systems for measuring small DC currents at
high voltage levels have been developed.

The transducer using the Pockels effect can mea-
sure DC currents with a lower limit around 0.5 µA. The
upper limit is given by the choice of the measuring re-
sistance.

The current to frequency transducer can measure
currents in the range 1 nA - 1 mA.

The development of the transducer systems is still
in progress.
References


Discussion

Harold Kirkham and Alan Johnston (Jet Propulsion Laboratory, Pasadena, CA): We would like to congratulate the authors on describing two useful-looking devices. We share with the authors the feeling that inexpensive and moderately accurate optical measurement systems have wide application possibilities in laboratory and field measurements. The wide dynamic range of the instruments described in this paper should make them extremely useful, and their simplicity should make them readily producible.

Our question relates to the suitability of materials such as the BSO used in the Pockels device for the high voltage environment. No doubt the authors of this paper are aware that another worker, also in Scandinavia, has been using a Pockels probe as a way to measure dc electric fields near high voltage busings. It has been reported that one of his field meters was involved in a flashover from the bushing, at which time the Pockels crystal was destroyed. This particular application used a rotating enclosure for the Pockels cell, so that there is a possibility that the destruction of the crystal was due to a failure in the mechanical construction used. It seems more likely, however, that the destructive energy had its origins in the flashover itself. While flashovers may not be commonplace in the real world of power systems, they are not unknown, and smaller corona activity certainly should be regarded as routine. Have the authors any observations on the suitability of high impedance, fragile optical materials such as BSO for application in real-world, outdoor power system measurements?

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OLE TONNESSEN

The authors would like to thank the discussers for their interest in this paper and for their insightful question.

Materials such as BSO have been used with good experience for measurement of voltage or electric field in high voltage environment. However, to the best of our knowledge, the long term behaviour of such measuring systems has not yet been reported. The potential applications can be divided into two main groups: 1) long term field service applications and 2) research and development applications.

Now, for both groups, the measuring device should be supplied with an overvoltage protection (approx. 1000V in our case) to prevent short time electrical breakdown of the Pockels device.

Furthermore, the measuring device should be designed in such a way that the occurrence of corona under service conditions is eliminated either - if possible - by proper shielding or by constraining the magnitude of the electric field around the measuring device to a maximum level.

However, dealing with experimental research and development work, one may unforeseenly exceed these limits, and as a consequence deteriorating partial discharges or striking plasma channels may destroy the measuring device. Thus, by choosing the right design of the measuring device with regard to the high voltage environment, it is considered that the technique is suitable for outdoor power system measurements. A further question may concern the long term resistance of such a measuring device against mechanical, thermal and chemical aging under service conditions. The years to come may give an answer to that.

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