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A wideband fiber-optic system for the measurement of ac high voltages is presented. The system is based on a capacitively coupled Pockels cell which works as a passive voltage sensor. The lower frequency limit is a few Hz and the upper is 150–230 MHz depending on the application. Other system characteristics are excellent electrical noise suppression, large voltage range, high input impedance, and ability to perform differential measurements separated from ground potential. Furthermore, the low cost, rugged design, and ease of operation make it suitable for measurements in a variety of high-voltage applications.

INTRODUCTION

Accurate wideband measurements of high voltages (HV) are difficult to perform, especially in electrically noisy environments. Conventional systems often have disadvantages and errors such as susceptibility to electrical interference, limited frequency bandwidth, and high cost.[1–3] This article presents an inexpensive optical wideband HV measurement system that is easy to apply to a wide range of HV measurement situations. The system utilizes a capacitively coupled Pockels cell as a passive HV sensor.

Electro-optical methods for HV measurements have many advantages compared to conventional methods, e.g., excellent electrical noise suppression, large bandwidth, good electrical insulation, good sensitivity, small size, and low cost.[3] The Kerr effect in nitrobenzene has been extensively used (Refs. 2 and 3 and references therein). Nitrobenzene offers a nearly frequency-independent Kerr medium and its large resistance to electrical breakdown allows direct coupling to the HV source. However, nitrobenzene is an uncomfortable liquid to work with and conventional parallel plate Kerr cells often exhibit limited bandwidth due to the large conductance of the nitrobenzene and large internal capacitances. Special arrangements such as coaxial and traveling wave Kerr cells have been designed for fast rise time.[3]

The linear electro-optic effect (Pockels effect) in certain crystals has been applied in a variety of HV applications (e.g., Refs. 3–8) and in electromagnetic field measurements (e.g., Ref. 9). Pockels cells offer larger bandwidths, and are small, and easy to use. However, commercially available cells have a limited voltage range due to electrical breakdown in the crystal. With a capacitive coupling[8,9] between the Pockels cell and the HV electrode, the voltage range of the HV measurement systems based on Pockels cells can be extended significantly. In a previous paper[8] such a system for laboratory measurements of fast spark voltage waveforms has been described. That system utilized a HeNe laser light source and in order to achieve good rf noise suppression the beam propagated freely ~20 m in the laboratory before impinging onto the photodetector. In the present article a fiber-optic HV measurement system using the capacitively coupled Pockels cell as voltage sensor is presented. The system shows larger bandwidth, less sensitivity to electrical interference, and an improved signal-to-noise (S/N) ratio compared to the system described in Ref. 8. The passive sensor allows differential measurements to be performed isolated from ground potential. Furthermore, the compact and rugged optical and electrical design makes it insensitive to environmental conditions. The system is thus suitable for use in the laboratory, as well as in an industrial environment. The system is constructed entirely from commercially available components.

I. SENSOR UNIT OPERATING PRINCIPLES

The principles of operation of the capacitively coupled Pockels cell sensor has been described in some detail in Ref. 8. Here a brief review will be given. The sensor unit is depicted in the right-hand side of Fig. 1.

The method relies on a voltage-induced birefringence in crystals such as KD*P, the Pockels effect (Ref. 10 or any optics textbook). If the Pockels cell is positioned between crossed polarizers and a $\lambda/4$ plate the relation between the

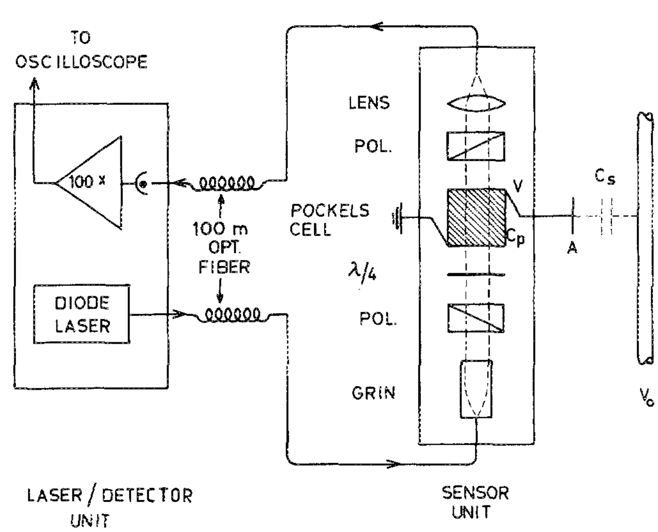

FIG. 1. The electrical and optical arrangement of the optical HV measurement system. The high voltage (V_0) affects the Pockels cell so that the sensor unit modulates the light intensity transmitted to the detector in proportion to V_0.

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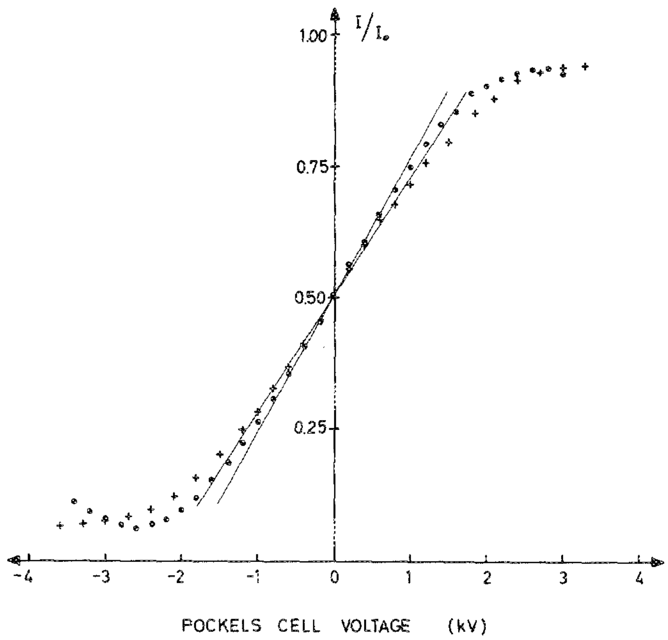

FIG. 2. The response of the sensor unit for frequencies above and below the piezoelectric resonance frequency of the Pockels crystal (~150 kHz). (●) Low frequencies. (+) High frequencies.

input intensity I_0 and output intensity I is

$$\frac{I}{I_0} = \sin^2\left(\frac{\pi}{2}\frac{V}{V_{\lambda/2}} + \frac{\pi}{4}\right), \quad (1)$$

where V is the voltage applied over the crystal and $V_{\lambda/2}$ is the half-wave voltage of the Pockels cell. The $\pi/4$ factor is an "optical bias" due to the $\lambda/4$ plate. Thus with $V=0$ the output intensity is $I_0/2$ and the application of an ac voltage produces an ac intensity variation around $I=I_0/2$. The relationship between the applied voltage and the output intensity is linear within $\pm 5\%$ for $V = \pm 0.17 V_{\lambda/2}$, which corresponds to $I = I_0/2 \pm I_0/4$.[7,8] The half-wave voltage for longitudinal KD*P Pockels cells is

$$V_{\lambda/2} = \lambda/2n_0^3 r_{63}, \quad (2)$$

where λ is the wavelength of the transmitted light, n_0 is the refractive index of the crystal material, and r_{63} the linear electro-optic coefficient. The electro-optic coefficient is independent of frequency above and below a region around the piezoresonance frequency of the crystal (~150 kHz). The coefficient is designated r_{63}^T for frequencies below the resonance and r_{63}^S above resonance. r_{63}^T/r_{63}^S for KD*P is approximately 1.20.[11] Measurements performed entirely on either side of the resonance region are not influenced by the difference in electro-optical coefficient.

Figure 2 shows I/I_0 for the HV measurement system for frequencies below and above the resonance frequency as a function of the voltage V over the Pockels crystal [see Eq. (1)]. Note the difference in the slope of the linear region and the difference in $V_{\lambda/2}$ due to the difference between r_{63}^T and r_{63}^S.

Many commercially available longitudinal Pockels cells have half-wave voltages of a few kV making measurements above ~1 kV nonlinear [see Eq. (1)]. By capacitively coupling the Pockels cell to the HV electrode (Fig. 1) the voltage V over the Pockels cell is reduced,

$$V = V_0[C_s/(C_s + C_p)], \quad (3)$$

where V_0 is the high voltage to be measured, C_p is the Pockels cell capacitance, and C_s is the stray capacitance between the HV electrode and an "antenna" A connected to one of the Pockels cell electrodes. Since both C_p and C_s are practically pure capacitances the voltage division is in principle frequency independent. The voltage V over the Pockels cell can simply be adjusted by changing C_s to give maximum response within the linear range of Eq. (1). Thus linear measurements are possible for voltages from ~100 V and upwards. Since the Pockels cell is always working near ground potential very high voltages can be measured without risking sparking in the crystal or electric discharges. Due to the small capacitance of the commercially available Pockels cell used in this paper ($C_p \approx 6$ pF) the stray capacitance C_s has to be very small in order to obtain suitable voltage division. Thus the electric load on the HV circuit due to the connected measurement system is very small.

The capacitively coupled Pockels cell sensor is a passive voltage sensor, which is connected to the electrical units of the HV measurement system only by optical fibers. Thus differential measurements separated from ground can be performed.

The disadvantage of the method is that the capacitive division has to be calibrated in each measurement situation. Calibration procedures will be discussed in Sec. III. As an alternative to capacitive coupling of a high-sensitivity Pockels crystal other crystal materials with lower electro-optic coefficient, e.g., quartz, can be used directly coupled to the HV electrode.[7] However, such systems cannot easily be adjusted for linear measurements of different HV levels and the voltage range is always ultimately limited by sparking along the crystal surfaces or electrical breakdown in the crystal.

II. SYSTEM DESIGN

Figure 1 shows the HV measurement system arrangement. The system consists of a sensor unit which is connected to a laser and detector unit by 100-m optical fiber. The signal is displayed on an oscilloscope or recorded by a transient digitizer. The design considerations are described in more detail in Ref. 12.

The light source of the system is a cw GaAlAs diode laser (Philips 513CQL-A) which produces 15 mW at $\lambda \approx 820$ nm. The optical bandwidth (FWHM) was measured to 2.5 nm. A diode laser was chosen due to its ease of operation, small size, low power consumption, long-term reliability, and a high and stable intensity output. The output intensity fluctuates less than 0.1%, thereby eliminating one source of noise in the previous system where the HeNe laser intensity varied ~0.5%.

The laser light is transmitted to and from the sensor unit by a 100-m 100-μm core graded index fiber having a dispersion of 100 MHz km (ASEA OC1). The 100-m fiber makes it possible to move the laser/detector unit away from sources of electrical noise. Such a long separation was not possible with the previous system due to the divergence of the HeNe laser beam and small vibrations that moved the freely propagating beam on the detector thereby inducing measurement errors. The large diameter fiber simplifies alignment while still yielding more than sufficient bandwidth (1 GHz). A GRIN lens collimates the light before it is transmitted through the sensor unit optics: two crossed Glan polarizers, a mica $\lambda/4$ plate, a KD*P longitudinal Pockels cell (Gsänger LM8), and a lens which focuses the beam on the output fiber. Due to the large diameter of the fiber the light beam in the sensor unit is somewhat divergent (15 mrad). This divergence in combination with the optical bandwidth of the laser results in that total extinction at $V = \pm V_{\lambda/2}/2$ is not achieved, which is shown in Fig. 2. However, the intensity interval ($I = I_0/2 \pm I_0/4$) used for the measurements is still linear to within $\pm 5\%$. The Pockels crystal is protected by an external spark gap not allowing voltages above ~ 3 kV to be applied over the crystal.

The photodetector is a biased pin diode (Hamamatsu S1188) connected to a dc coupled $\sim 100\times$ fast amplifier (ORTEC AN302/N) with a rise time of ~ 1.5 ns. The optical system transmits $\sim 2\%$ of the input laser intensity making $I = I_0/2$ correspond to ~ 300 mV at the oscilloscope.

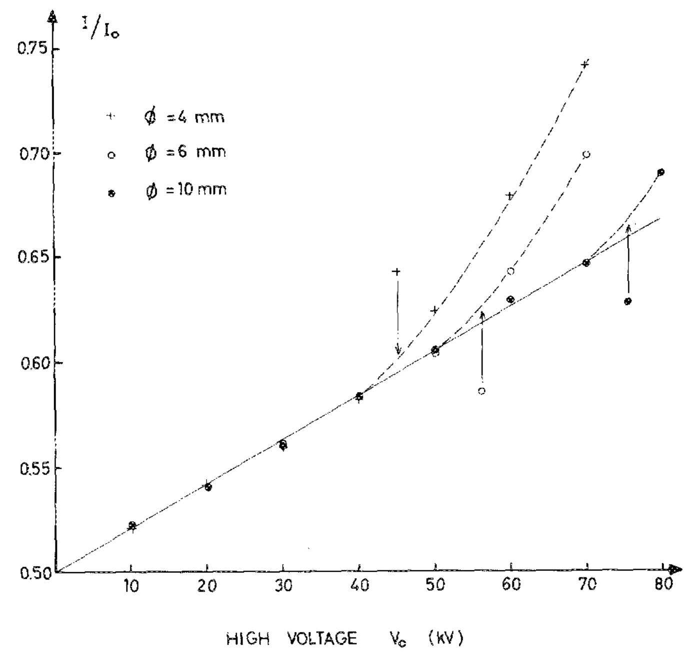

FIG. 4. The effect on the capacitive division of corona discharges on a HV line. The arrows indicate the onset of an audible corona discharge on the rods of different diameters (Φ).

III. MEASUREMENTS AND DISCUSSION

The low-frequency cutoff is determined by the $R_p C_p$ time constant, where R_p is the internal resistance of the Pockels cell. In Ref. 8 the time constant was determined to be 0.4 s. The performance of the system at low frequencies and at very high voltages was tested in a gas-insulated switch gear (GIS) component at the ASEA GIS production plant. Figure 3 shows a recording of a 50-Hz 460-kV rms waveform. In this measurement the capacitive coupling was optimized for higher voltages making 630 kV correspond to 20 mV on the oscilloscope.

In low-frequency measurements care has to be taken to eliminate the influence of possible corona discharges on the HV line. Since a corona discharge increases the effective electric diameter of the HV electrode, the capacitance C_s also increases. Figure 4 shows the nonlinear behavior of measurements with a Pockels cell capacitively coupled to 2-m-long brass rods of different diameters (4, 6, and 10 mm) carrying 50-Hz voltages. In each measurement a rod was suspended horizontally in the laboratory and the Pockels cell with its antenna was positioned ~ 1.5 m away from the rod (see Fig. 1). By changing the size of the antenna the capacitive coupling was adjusted to give the same Pockels cell signal for all the rods at low voltages. The arrows indicate the onset of an audible corona discharge for each rod.

The high-frequency performance of the system was tested at the Uppsala Institute of High Voltage Research using their high-voltage cable generator.[13] The generator produced 1-μs-long square HV pulses by discharging a charged 100-m coaxial cable over a 50-Ω water resistor. The dis-

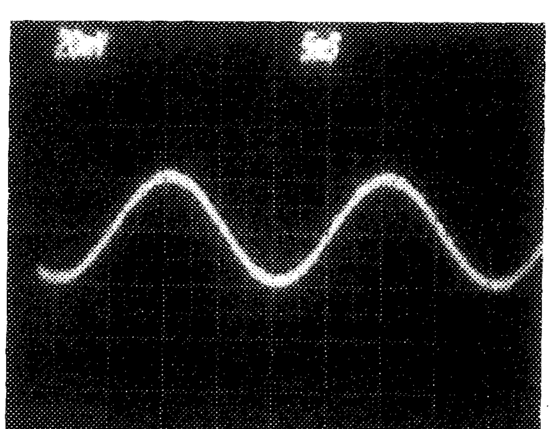

FIG. 3. Recording of a 50-Hz 460- kV rms waveform (630 kV/div).

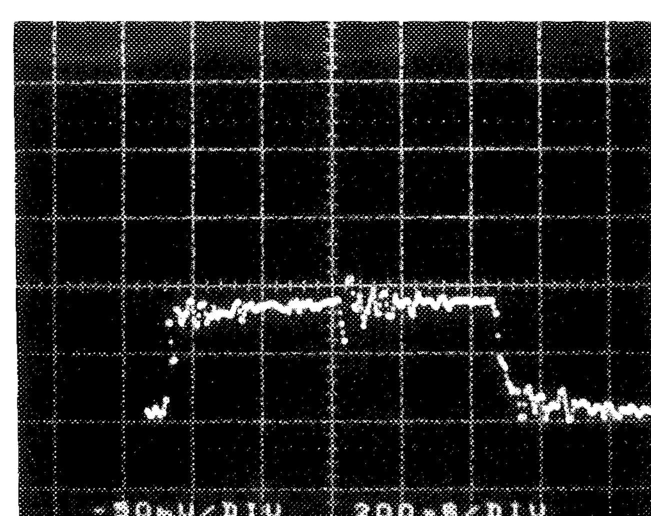

FIG. 5. Recording of a 50-kV pulse (31 kV/div).

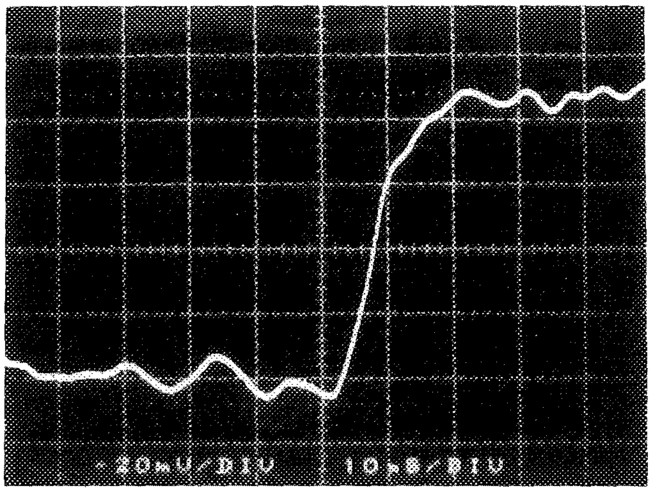

FIG. 6. Recording of the leading edge of a 7.5-kV pulse (1.70 kV/div).

charge is controlled by an air- or SF_6-filled pneumatically controlled spark gap. Measurements were performed for voltages between 3 kV and the upper limit of the water resistor, 50 kV. Figure 5 shows the recording of the HV measurement system for a 50-kV pulse. Some residual rf interference was observed since the laser/detector unit was positioned only $\sim$20 m from the cable generator. In order to compare the HV measurement system with conventional methods measurements were performed at lower voltages. Figure 6 shows the leading edge of a 7.5-kV pulse. The measurements were recorded with a fast storage oscilloscope (Iwatsu TS8123, $t_r = 3.5$ ns) yielding a total rise time of $\sim$4 ns. The result was compared with theoretical calculations and measurements with a conventional probe (Tektronix PE6015). The results agreed very well if the longer total rise time ($t_r \approx 6$ ns) of the conventional probe was taken into account.

Due to the lack of a sufficiently fast conventional HV measurement system for reference measurements the upper-frequency limit of the HV measurement system could not be determined directly using HV pulses. Thus an indirect determination of the frequency response was performed.

The upper frequency limit of the HV measurement system is determined by the combined rise time of the fiber-optical link, the photodetector, and the electronic amplifier added to the frequency limit of the capacitively coupled Pockels cell sensor unit. The optical and electronic rise time was determined by transmitting repetitive picosecond (ps) dye laser pulses ($\lambda \approx 580$ nm) through the fiber-optic measurement system and recording the impulse response of the system with a fast (1 GHz) sampling oscilloscope. The rise time was determined to be $\sim$1.5 ns (230 MHz) and the fall time somewhat longer. Tests showed that the rise time was entirely determined by the photodetector and the amplifier. The influence of the dispersion of the optical fiber was negligible. The difference in wavelength between the diode laser and the ps dye laser is assumed not to change the result.

The transit time of the light through the Pockels cell and the response time of the Pockels crystal to an electric field is very fast and does not influence the system rise time.[14] However, the capacitive coupling of the Pockels cell has to be considered. The capacitive division [Eq. (3)] should in principle be frequency independent since both the Pockels cell and the coupling between the antenna and the HV electrode are pure capacitances. However, the frequency performance is influenced by the inductances L of the wires connecting the Pockels cell with the antenna and the ground. Thus a series resonance circuit is formed by C_p, C_s, and L. Using a Hewlett–Packard 4191A rf impedance analyzer (1–1000 MHz) the frequency performance was determined for a setup corresponding to the one used in the measurement of Fig. 6. This arrangement can be considered a normal measurement setup where no special care was taken to shorten the wires in order to reduce inductances (approximately 20-cm wires). The voltage division was found to be frequency independent below 200 MHz corresponding to a rise time of $\sim$1.8 ns yielding a total rise time of the HV measurement system of $\sim$2.3 ns (150 MHz). Often shorter wires can be used (see Ref. 8) thereby extending the frequency range significantly. Furthermore, since C_s is much smaller than C_p the frequency dependence of the series resonance circuit is determined by the LC_s resonance. Therefore, the upper frequency limit is increased when higher voltages are measured since C_s has to be decreased in order to keep the voltage over the Pockels cell within the linear range. Thus the rise time of the system in most applications is 1.5–2.5 ns, where the lower limit is set by the photodetector and the electronic amplifier.

The accuracy of the measurements is determined by several factors. Naturally, the voltage over the Pockels cell has to be within the linear range to obtain errors less than $\pm 5\%$. Accurate calibration of the voltage division is neccessary (see below) and both the calibration measurements and the actual HV measurements are affected by the S/N ratio. In the HV measurement system the noise level is entirely determined by the photodetector/amplifier noise, which is $\sim 1\%$ rms of the voltage corresponding to $I_0/2$ at full bandwidth, and possible residual rf interference. Errors due to possible long-term changes in the laser diode output intensity and optical fiber transmission line losses are easily eliminated by continuously monitoring the dc level corresponding to $I = I_0/2$. The accuracy of measurements in the 150-kHz–1-MHz range is limited due to piezoelectric oscillations in the Pockels cell crystal.[8] However, measurements in this frequency region can be performed by exchanging the fast Pockels cell used in the current system for a somewhat slower light modulator without piezoresonances (e.g., the also commercially available Gsänger LM020). Alternatively, the crystal oscillations can be damped in a similar way, as is done in the field of ultrasonic transducers.[15]

It should be noted that the electro-optic coefficient is temperature dependent. Thus the crystal temperature has to be held constant within approximately ± 5 °C in each experimental situation in order to achieve errors less than $\pm 5\%$.[11]

In each experimental situation the capacitive division has to be calibrated experimentally using conventional HV measurement equipment. Due to the linear response the calibration can be performed at lower voltage levels than those eventually measured, thereby reducing the voltage requirements of the conventional equipment. Accurate calibrations with low voltages require a good S/N ratio. Thus for this system ($S/N \approx 60$) measurements of, e.g., 60-kV transients can be calibrated at 10 kV with a S/N ratio of 10. The calibration can often be performed with a reduced bandwidth of the detection system which increases the calibration S/N ratio. In many applications HV transients are measured on a HV line which already carries a low-frequency voltage (e.g., 50-Hz) of known voltage. Due to the low lower-frequency limit of the sensor unit it is possible and convenient to calibrate the transient measurement system against the known 50 Hz voltage. Correction for the difference between the high- and low-frequency electro-optical coefficient, r_{63}^S and r_{63}^T, respectively, must be made.

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