INTERNATIONAL SYMPOSIUM ON HIGH VOLTAGE ENGINEERING YOKOHAMA, JAPAN AUGUST 23-27, 1993



54.04

INVESTIGATION OF THE EFFECTS OF AGING ON THE CALIBRATION OF A KERR-CELL MEASURING SYSTEM FOR HIGH VOLTAGE IMPULSES*

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Abstract

Kerr-cell measuring systems can be used for high-voltage measurements from direct voltage up to impulses with a few nanoseconds risetime. In principle, this allows a measuring system for impulses to be calibrated at high-voltage using direct or alternating voltage which can be measured with a smaller uncertainty than is needed for impulse measurements. Unfortunately, the liquid normally used in such systems, nitrobenzene, degrades with time. This paper reports on an investigation into methods of calibrating an aged Kerrcell so that a measuring system based on a Kerr-cell could be used as a Reference Measuring System. The methods investigated include direct voltage calibration and impulse calibration with direct voltage bias. The repeatability of measurements using a fixed geometry to determine the voltage scale factor was also investigated. Results from both approaches are presented and recommendations are given for reference measuring systems.

1. Introduction

Present proposals for the revision of International Electrotechnical Commission (IEC) standards on measuring systems call for the use of Reference Measuring Systems to characterize the measuring systems used in industrial test facilities. The accuracy required from Reference Measurement Systems is 1% for the measurement of peak voltage. Previous work has shown that measuring systems based on electro-optic Kerr cells which have been freshly filled with purified nitrobenzene can deliver the required uncertainty for impulse voltage measurements, suggesting that Kerr systems may be viable Reference Measuring Systems /1–2/.

Early work on the Kerr effect in nitrobenzene showed that the conductivity of the prepared sample was a good measure of the suitability of the sample for

• NRC 35928

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use in a cell used under direct voltage and that values of the Kerr constant K_c obtained using short pulses of less than 10⁻⁴ seconds duration were virtually independent of sample purity over the range tested. The Kerr constant, K_c relates the induced birefringence to the square of the electric field, E:

$$n_{\perp} - n_{\parallel} = \lambda K_{\rm c} E^2 \tag{1}$$

where λ is the wavelength of the light. Commercial grade nitrobenzene has a conductivity of about 10⁻⁷ (Ω cm)⁻¹ and can be readily purified to give a conductivity of about 10⁻⁹ (Ω cm)⁻¹; special techniques have been used to produce samples with conductivities as low as 5 × 10⁻¹² (Ω cm)⁻¹. Published work shows that K_e, measured using direct voltage, goes from 2.4 × 10⁻¹² mV⁻² to 4.6 × 10⁻¹² mV⁻² for a reduction in conductivity from 2 × 10⁻⁸ (Ω cm)⁻¹ to 1 × 10⁻¹⁰ (Ω cm)⁻¹ while a value of 4.2 × 10⁻¹² mV⁻² ±1% was obtained from pulse measurements on samples whose conductivities ranged from 1.3 × 10⁻⁷ (Ω cm)⁻¹ to 4 × 10⁻¹¹ (Ω cm)⁻¹ /1/.

2. Kerr Cell Systems

Two types of Kerr cell were used in this work, one with parallel plate electrodes and one with disk electrodes. An example of a Kerr cell system is shown in Fig. 1 together with a resistor divider in parallel.

This Kerr cell (identified as cell B) has parallel plate electrodes (with rounded edges) which give a uniform field region between the electrodes. The length, L, was chosen such that L>>D to reduce fringe effects (D is the separation between the plates). The laser beam is transmitted along the long axis of the cell. The polarizer is set at 45° to the electric field between the plates and the analyzer is rotated to give minimum light transmission at zero electric field, i.e., at 90° relative to the axis of the polarizer. When an electric field is applied between the plates a phase shift ϕ is produced between the



Figure 1. Calibration of Kerr cell B against a reference measuring system for direct voltage.

component of the light beam polarized parallel to the field in the cell and that polarized perpendicular to the field in the cell. The induced phase difference between the two components changes the polarization of the beam from linear to elliptical so that some light is transmitted to the photomultiplier. The intensity of this light, I, is given in terms of the maximum transmitted intensity (I_m) by

$$I = I_{\rm m} \sin^2 \left(\frac{\pi}{2} \left(\frac{V}{V_{\rm m}} \right)^2 \right) \tag{2}$$

where $V_{\rm m}$ is defined as the half-wave voltage, i.e., it is the voltage required to produce a phase shift ϕ of $\pi/2$, and the fringe number N is defined as $(V/V_{\rm m})^2$.

Many simplifying assumptions have been made in deriving (2) and these have been carefully analyzed by previous workers (e.g. /2-4/ and references found therein). However in this work, where the Kerr cell system is being evaluated as a transfer standard, the most crucial of these is the assumption of a uniform field between the plates. A constant but non-uniform field would give no problem (provided that temperature corrections are applied to allow for any ohmic heating and changes in ambient temperature /4/) but non-uniformities are caused by charge injection which varies with the applied voltage and with time. In addition, this injected charge leads to electrohydrodynamic effects causing turbulence in the nitrobenzene. The effects of charge injection are discussed further in /5/.

The other cell, K_2 , used in this study has disk electrodes (disk diameter 3.18 cm and gap length 2.54 cm) enclosed in a polytetrafluoroethylene (PTFE) container which has two diametrically-opposed windows (see Fig. 2). The cell is filled with nitrobenzene and immersed in an oil-bath to provide sufficient insulation to prevent discharges over the surface of the cell. A metal rod provides a connection between the upper electrode of the Kerr cell and the external connection point C. A mercury-in-glass thermometer is mounted near the bottom of the oil-bath.

This paper reports an investigation of how Kerr cells containing aged samples of nitrobenzene can be calibrated. The techniques used were: (1) direct voltage calibration, (2) impulse calibration with a direct voltage

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Figure 2. Free-standing Kerr cell, K2.

bias, and (3) impulse calibration against a Reference Measuring System based on a resistor divider.

3. Direct Voltage Calibration

Investigations of direct voltage calibration were made on cell B which has a well-established history. This cell has been used for several years for calibrating resistor dividers with impulses. The cell had been filled with a fresh sample about three months prior to the start of these tests. Applying a direct voltage led to a direct current which increased as the voltage setting was increased but little voltage was developed across the cell. Considerable turbulence was observed corresponding to charge injection and electrohydrodynamic effects. The resistance of the cell was checked under pulse conditions: a 100 V pulse was applied to a voltage divider circuit consisting of a resistor in series with the cell. The voltage drop across the resistor was recorded and measured on an oscilloscope. The resistance of the cell was calculated from the known input voltage, the known resistance of the resistor, and the measured voltage. The pulse was applied for less than 10⁻⁴ s to avoid charging effects. The cell resistance found in this manner was 800 k Ω corresponding to a conductivity of 2 × 10⁻⁸ (Ω cm)⁻¹. Similar results were obtained with K_2 which had been filled about a year before and at the time of this test contained nitrobenzene with a conductivity of 4 × 10⁻⁸ (Ω cm)⁻¹.

Cell B was evacuated and then filled with freshlypurified nitrobenzene repeatedly until the measured conductivity of the nitrobenzene in cell B was less than $3 \times 10^{-9} (\Omega \text{ cm})^{-1}$. When the direct voltage was applied to cell B the current increased rapidly then slowly decreased. In operation the current through the cell was kept low by controlling the rate at which the applied voltage was increased to limit the total current through the cell and the resistor divider in parallel to 2 mA: after each voltage increment the current was allowed to decay before the voltage was increased further. Temperature was measured using two mercury-in-glass thermometers, one in the nitrobenzene and one in the oil-bath in which cell B was immersed. These temperature measurements allowed the effect of ohmic heating in cell B to be separated from changes (if any) in ambient temperature. An example of a dc calibration where data were recorded manually is shown in Fig. 3 together with a least-squares fit of equation (2) to this measured data /6/.

In another method, data were recorded on a digital oscilloscope and V_m was evaluated at the maxima, minima, and midpoints of the displayed curve as the quotient of the voltage measured with the dc voltage divider and \sqrt{N} where N is the fringe number. As has been found previously and attributed to charge injection causing a non-uniform field /3/, the values for V_m varied with N: low fringes have greater uncertainty because of the low value of N. Values averaged over five fringes for N in the range 5 to 25 are given in Table 1, along with their experimental standard deviations (1 σ).

Table 1. Kerr cell constant, V_m , of cell B from calibration with direct voltage.

| Fringes used to calculate value | V. | Experimental Standard Deviation (1 σ) | |
|---------------------------------------|------|--|-----|
| | (V) | (V) | (%) |
| 4.5 to 9 | 6212 | 72 | 1.1 |
| 9.5 to 14 | 6310 | 51 | 0.8 |
| 14.5 to 19 | 6412 | 25 | 0.4 |
| 20.5° to 25 | 6438 | 15 | 0.2 |
| Mean Value of V_m | 6343 | 103 | 1.6 |

^{*}There was insufficient data in the region of the 20th peak to read it accurately.

It can be seen that there is an increase in the value of $V_{\rm m}$ with fringe number and a decrease in the estimate of the standard deviation. The agreement with the value of 6417 V ±1% (3 σ) found by comparison with an impulse calibration against a small oil-insulated precision resistor divider housed in the same oil bath is acceptable (difference <1.2%) for the mean value taken over the range of fringe numbers 4.5 to 25 and very good (difference <0.3%) for the ranges 14.5 to 19 and 20.5 to 25.





The reduction in the standard deviation of V_m with increasing N as shown in this table is in agreement with the theoretical uncertainty reported in /6/, where it is shown that the relative uncertainty $\delta V_m/V_m$ is inversely proportion to the fringe number N.

In these calibrations it was found that the variation in recorded intensity decreased with fringe number: this can be seen in Fig. 3 but the increase becomes even more marked at higher fringe numbers with the maximum-to-minimum variation at $N \sim 25$ being only a quarter of the initial maximum-to-minimum variation. This phenomena has been previously observed and was attributed to charge injection causing non-uniform fields /3/. A quantitative treatment has been published in /5/. A beam spreader was inserted to give uniform illumination over the entire inter-electrode space and observations were made using a video camera and recorder. For a uniform field the entire area should become brighter as the voltage is increased to V_m and then darker as the voltage is increased to 2 Vm etc.. Observations at several times V_m showed several fringes in the gap between the electrodes confirming that the field is not uniform (see Fig. 4).

4. Direct Voltage Bias

The base plate of the cell was isolated from ground by mounting it on four PTFE insulators. The bias was applied via a filter consisting of a capacitor to ground and a resistor, R_i , to isolate the dc source. With this circuit the impulse dividers could not be used in parallel with the Kerr cell, K_2 , because they would be in series with R_i and act as a voltage divider.

Various values of bias were used and impulses (positive and negative) were applied to the Kerr cell, K_2 , for each value of bias used. Only small values of bias could be used as quite large currents flowed through the Kerr cell, K_2 , because of its high conductivity. For the case of an impulse, peak value V_1 , applied with zero bias to give N_1 fringes and with a bias of V_B volts ($V_2=V_1-V_B$) to give N_2 fringes, equation 1 can be written:

$$V_1 = \sqrt{N_1} V_{\rm m} \tag{3}$$

and

$$V_2 = \sqrt{N_2} V_{\rm m} \tag{4}$$

Combining these equations gives $V_{\rm m}$ as a function of the bias voltage $V_{\rm B}$:

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Figure 4. Fringes in Kerr cell B.

$$V_{\rm m} = \frac{V_{\rm B}}{\sqrt{N_1} - \sqrt{N_2}} \tag{5}$$

The combined standard uncertainty of the determination depends on the standard uncertainties in $V_{\rm B}$, N_1 , and N_2 /8/. To enhance the resolution, it was necessary to use as high a bias as was feasible. The resolution can be increased by comparing records of impulses of the same magnitude taken with negative bias and with positive bias. In practice the bias voltage drifted because of the high conductivity of the Kerr cell, K₂, and so readings were taken of the bias at each impulse. Results are shown in Table 2.

Table 2. Values of V_m for directly-coupled bias.

| Bias Voltage (kV) | Charging Voltage of Impulse Generator (kV) | Vm (kV) |
|-------------------------|--|------------|
| 7.2961 ¹ | 58 | 55 |
| 11.482 ¹ | 58 | 49 |
| 14.514 ¹ | 58 | 54 |
| 7.2405 | 70 | 57 |
| 11.395 | 70 | 47 |
| Mean value of V_{\pm} | 52.4 | |
| Experimental stand | 4.2 | |

¹Taken by combining records from positive and negative bias.

Because the directly-coupled bias was limited to quite small values, efforts were made to reduce the current injection in the Kerr cell, K_2 , by isolating the unbiased electrode from ground through a small, low capacitance air gap. The air gap was made long enough to withstand the direct voltage bias but short enough to spark over when the impulse was applied. With this system the current in the Kerr cell, K_2 , was considerably reduced and the bias voltage was now limited by the breakdown voltage of the high voltage capacitor used as a filter. Calibrations were performed for bias voltages in the range of 40 kV to 50 kV; results are given in Table 3.

Table 3. Vm for unbiased electrode floating.

| Bias Voltage (kV) | Charging Voltage of Impulse Generator (kV) | Vm (kV) |
|-------------------------|--|------------|
| 40.535 | 70 | 55.2 |
| 49.712 | 70 | 55.5 |
| 50.194 | 70 | 56.2 |
| Mean value of V_m | 55.6 | |
| Experimental stand | 0.5 | |

5. Impulse Calibration

Impulse calibration has been used for many years to characterize Kerr-cell systems /6/ using the system shown in Fig. 1 with the dc source replaced by an impulse generator and the digital multimeters replaced by an oscilloscope. Additional work on impulse calibration is described in a companion paper /7/. While aging affects the dc performance of Kerr cells it has been found that the behavior under impulse is constant within 1%.

6. Conclusions and Future Work

The work on calibration with direct voltage has shown that this technique can only be applied to cells which have been freshly filled with purified nitrobenzene. Areas for further study are the use of Kerr liquids which do not age as rapidly and the use of passivated electrodes to limit charge injection. Calibration of an aged cell using direct-voltage bias can only achieve the desired accuracy when the un-biased electrode is allowed to float. Since impulse calibration is independent of cell aging, it is preferred to the direct voltage methods. This work shows that Kerr-cell systems can be calibrated with sufficient accuracy to be used as Reference Measuring Systems for full lightning impulses using a scale factor established either by direct-voltage calibration of a newly-filled cell or by impulse-calibration of an aged cell.

Acknowledgments

Financial assistance by NIST under Cooperative Agreement No. 70NANB9H0967 is gratefully acknowledged by T.R. McComb.

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