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COMPARATIVE MEASUREMENTS OF HIGH-VOLTAGE IMPULSES USING A KERR CELL AND A RESISTOR DIVIDER*

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Abstract

Recent proposals in committee drafts of IEC TC42 have placed greater emphasis on the use of comparative measurements as a method of qualifying impulse measuring systems. This paper describes some further investigations of comparative measurements where a Kerr-cell system is compared against a system based on a resistor divider. The paper describes the experimental techniques used to make comparative measurements, and the results of tests on the linearity of the systems are presented. Finally, recommendations are made for the use of comparative measurements in qualifying impulse measuring systems.

1. Introduction

Present proposals for the revision of IEC Standards on measuring systems call for the use of Reference Measuring Systems which are themselves traceable through national or international comparisons. Independent laboratories, such as National Laboratories, will usually establish Reference Measuring Systems through five steps: (1) measuring the scale factor (usually at low voltage and low frequency), (2) using the unit step response to estimate the time range over which the scale factor is constant, (3) establishing the linearity of the system for the range of voltage to be measured, (4) checking that the method of comparison is valid, and (5) comparing it with a system which has been established in a national or international comparison. However for industrial test facilities it is only necessary to perform step five at set intervals (supported by Performance Checks to show that the assigned Scale Factor is still valid). This paper reports on work performed at the National Institue of Standards and Technology (NIST) establishing two Reference Measuring Systems, one based on a Kerr-cell and the other based on a resistor divider, against another resistor-divider system which had been established as a Reference Measuring System in an International comparison /1/(R_3 in this paper is identified as NBS3 in /1/).

Because the measurement technique used in the Kerr-cell system is different to that used in divider-based systems (resistor, capacitor or mixed) the systematic errors can also be expected to be different and the comparison of these systems can provide a test of whether the systematic errors have been adequately treated. Based on the work reported in the following sections when measurements are made with the two measuring systems at right angles with matching resistors, the required measurement uncertainties are achieved.

2. Description of Systems

The basic design of resistor dividers is well-established from the work of several groups /2/. The high-voltage arm consists of one or more low inductance, wire resistors which are mounted vertically in-line with a shielding electrode. Single resistors are wound on a uniform spiral using two parallel windings wound in opposite directions to minimize inductance. The shielding electrodes are designed to give an approximately uniform field. When multiple resistors are used their values are chosen to match the residual non-linearity of the field as calculated in reference /3/. For R_1 three resistors whose nominal values were 2500 Ω, 3500 Ω and 4000 Ω, were used. The lower limit to the resistance of a divider is set by the requirement of not overloading the generating circuit and values from 1 kΩ to 3 kΩ for each 100 kV of source voltage are usually used. Once the resistance is chosen the best response that can be obtained is set by the height of the divider with smaller dividers being faster. Several designs have been published of reduced-size fast dividers which were insulated by immersion in pressurized gas or in oil to increase their voltage rating /2,4/.

* NRC 34188

The dividers used in this work were: (1) R_3, an air-insulated, 10 kΩ, resistor divider rated at 300 kV; (2) R_4, an oil-insulated, reduced-size, 10 kΩ, resistor divider rated at 300 kV; and (3) R_1, an air-insulated, 10 kΩ, resistor divider rated at 1 MV (R_1 was used only for linearity tests which went beyond the rating of the other dividers).

The scale factor of an impulse measuring system based on a resistor divider can be determined as the product of the scale factor (ratio) of the divider (including any matching or damping resistor) with the scale factor (ratio) of any additional attenuators and with the scale factor of the recording instrument (a 10-bit, 100 megasample/s digitizer was used in this work). The scale factor of the digitizer is determined from the Pulse-Level-Line method using a precision pulse generator previously developed at NIST for this purpose /4/.

The matching resistor, r_d, is chosen by a compromise between reducing oscillations in the step response and obtaining a fast initial response. The resistance of the high voltage arm is about 10 kΩ. The low voltage arm consists of a resistor mounted between the low end of the high voltage arm and ground in parallel with a cable and its terminating resistance which will include any attenuators used. The attenuators used consist of high power resistors in well-shielded boxes and the values are chosen to give an input resistance of 50 Ω when they are terminated in 50 Ω. Attenuators with nominal values of 2X, 3X, 4X and 6X were used. The Kerr-cell used in this work is described in detail in a companion paper /5/.

3. Step Responses

Step responses of systems based on resistor dividers were taken with a mercury-wetted relay. In all cases the same lead length was used and the matching resistor was moved to the input of the step generator by bending the high voltage lead. This modification and the use of a low input impedance step change the system's response. Although the effects of this modification will be smallest when matching resistors are used at the input of the high-voltage lead, the step response of the modified system should only be used to estimate the performance of the measuring system. The step response of the three systems (modified as described above) used in this work, were convolved with two double-exponential impulses simulating full lightning impulses, a 1.2/50 impulse and 0.9/50 impulse using a program previously developed at NIST /6/. The predicted errors are listed in Table 1 (ΔV is the error in peak voltage, ΔT_1 is the error in front time).

The step response of the Kerr-cell was taken by applying a chopped impulse: the applied voltage was adjusted to give just less than one fringe. The measured voltage collapse has to be corrected for the sine-squared dependence before it is used. This measured collapse (of a negative impulse) is shown in Fig. 1, together with the step responses of systems based on R_3 and R_4. Because the collapse is faster than both responses, any response time error in the Kerr-cell system can be expected to be smaller than those predicted in Table 1.

Table 1. Estimates of errors calculated by convolving the step response of each system with a double-exponential input.

Resistor	Type of impulse used: 1.2/50		0.9/50	
Divider	ΔV (%)	ΔT_1 (%)	ΔV (%)	ΔT_1 (%)
R_1 (r_d=0Ω)	0	−0.3	0.0	−0.1
R_3 (r_d=405 Ω)	0	1.0	−0.1	1.1
R_4 (r_d=396 Ω)	0	1.2	−0.1	1.3

4. Linearity

Linearity of the dividers used was ensured by careful design according to established principles and checked by comparing the measured voltage to the measured charging voltage of the impulse generator. With this method it was necessary to ensure that constant conditions of charging were maintained. At each setting a number (usually 10) of impulses were recorded and the mean value was taken. Results for R_1 are given in Table 2: this data can be fitted to a straight line with a correlation coefficient of 0.99998 and each point is within 1% of the fitted line.

Table 2. Linearity of R_1.

Charging Voltage (kV)	Measured Impulse (kV)	Experimental Standard Deviation (%)	Number of Impulses
20	89.4	0.3	10
40	180.2	0.3	10
60	268.4	0.1	10
80	356.3	0.1	9
100	444.5	0.2	5

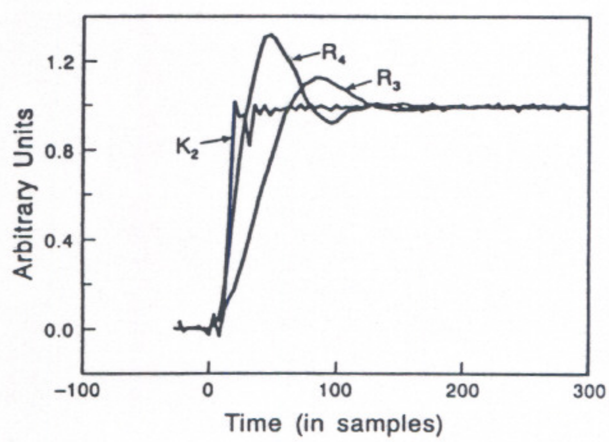

Figure 1. Step responses of systems based on R_3 and R_4 together with the measured voltage collapse on a Kerr-cell system (time scale 5 ns/sample, zero-referenced to trigger).

Table 3. Linearity of NRC 1MV divider.

Charging Voltage (kV)	Measured Impulse (kV)	Difference from Fitted Line (%)
25	133.8	-0.3
37	198.9	-0.05
50	269.3	-0.05
75	406.3	0.5
87	467.5	-0.3
100	539.0	-0.04

Similar tests were made with a 1MV divider at NRC and the results obtained are given in Table 3: this data was fitted to a straight line with a correlation coefficient of 0.99997 and each point is within 0.5% of the fitted line. This test gives increased confidence in the linearity of the divider because it is unlikely that both the divider and the impulse generator will be nonlinear in compensating ways. The range of applicability has only been verified to about 500 kV but other workers have shown the method can be used up to 2.5 MV /3/.

The linearity of a Kerr-cell system based on K_2 was checked against R_4 for the range of impulse voltages which gave from 10 to 16 "fringes". Results are presented in Table 4: these results ($\sqrt{N}$ against peak voltage) are all within 1% of the fitted straight line which gives V_m= 55.2 kV at a nominal temperature of 23°C.

Table 4. Linearity of K_2.

Number of Fringes (N)	$\sqrt{N}$	Peak Voltage (kV)
10.00	3.162	177.3
10.58	3.253	181.0
11.00	3.317	185.6
11.55	3.399	190.5
13.85	3.721	208.4
15.96	3.995	221.5
16.83	4.103	229.7

These results show that two of the methods proposed in the draft standards (comparison against charging voltage, comparison against an approved system) can give an uncertainty within the required limits.

5. Comparative Measurements

Comparative measurements were made using two systems simultaneously (in the circuit shown in Fig. 2) to measure the parameters of full lightning impulses. Some results obtained with the resistor-divider systems are given in Table 5. The good agreement of peak values and front times indicates similar behaviour of the air-insulated divider (R_3) and the oil-insulated divider (R_4).

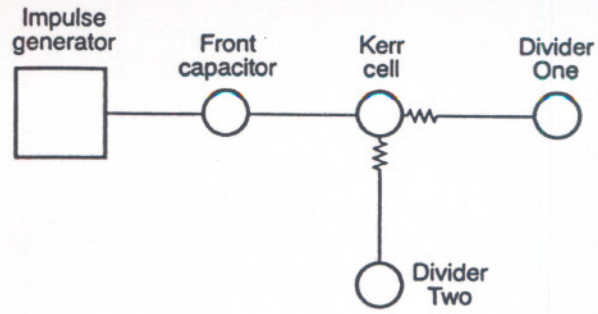

Figure 2. Circuit for comparative measurements.

Table 5. Comparison of two systems based on resistor dividers.

Parameter	R_3	R_4	Difference
Peak value	(kV)	(kV)	(%)
	216.6	216.3	0.1
	214.3	215.7	-0.7
	79.1	79.7	-0.8
	65.6	65.7	-0.2
Front time	(ns)	(ns)	(%)
	1039	1026	-1.3
	1017	1015	0.2
	897	891	0.7
	1099	1094	0.5

Kerr-cell systems were set up as the test object in the circuit of Fig. 2 and calibrated using full lightning impulses. Examples of the waveforms recorded are shown in Fig. 3 and an expanded view of the first part of Fig. 3 is shown in Fig. 4. Both waveforms are recorded with 1200 samples taken at 10 ns/sample followed by 2896 samples at 100 ns/sample: this recording mode gives an apparent change of slope at the breakpoint between the two sampling rates but allows both high time resolution on the front and the complete impulse to be recorded on a shorter record than if uniform sampling were used throughout the record. The record

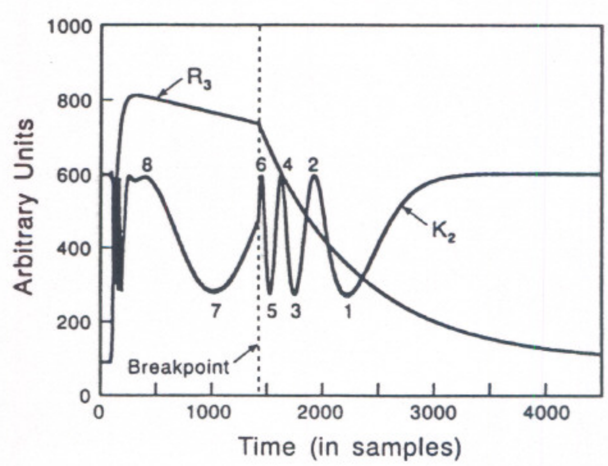

Figure 3. Records of a full lightning impulse measured on R_3 and K_2.

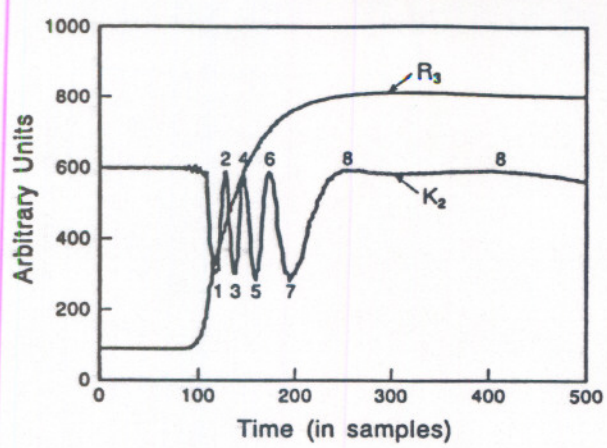

Figure 4. Expanded view of Fig. 3 showing front of the impulse.

from the resistor-divider system shows the usual double-exponential modified by the change in sampling rate: the record from the Kerr-cell system shows oscillations in light intensity where each change in intensity from maximum-to-minimum or minimum-to maximum corresponds to a change in voltage of V_m, the cell constant. Methods of determining V_m are discussed in a companion paper /5/. Calibration of K_2 against R_3 gave V_m = 55.8 kV with an experimental standard deviation of 0.26 kV at a nominal temperature of 23°C. The cell constant is a function of temperature (see /7/), but for the small range of temperatures of less than 3°C occurring in this work the temperature correction has been neglected because the temperature of the nitrobenzene was not measured directly: the effect is included in the random uncertainty.

6. Conclusions

Work on establishing the uncertainty of Reference Measuring Systems has shown that when the two systems, based on resistor dividers, are arranged at right angles to each other and used with matching resistors at the input of the high-voltage lead then the agreement of the two systems for measuring full lightning impulses is within that proposed for international standards (1%). In addition it has been shown that two of the techniques proposed to verify the linearity can provide the required relative accuracy. A system based on a Kerr-cell has been calibrated by a comparison against a system based on a resistor divider and it has been shown that the measurements are repeatable within the required uncertainty. Based on the work reported here and in the cited references when measurements are made with the two measuring systems at right angles as shown in Fig. 2 and matching resistors, the required measurement uncertainties are achieved. Other measuring system configurations need to be tested to verify that the uncertainties can be achieved.

Acknowledgments

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