UNCERTAINTY OF PEAK-VALUE MEASUREMENT OF LIGHTNING-IMPULSE HIGH VOLTAGE BY NATIONAL-STANDARD-CLASS MEASURING SYSTEM

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Abstract: The standard measuring system for lightning-impulse high voltage, which is composed of a voltage divider, calibrators and a digital recorder, is constructed. Some performance tests have been carried out and the overall uncertainty of peak voltage measurement is evaluated to be 0.3 % with the coverage factor, *k*, of 2. This is less than the 1/3 of the requirement for a reference measuring system. Furthermore, this value is as small as those of national standards of other advanced countries.

1 INTRODUCTION

It is required in IEC60060-2 [1] that measuring systems used for high-voltage impulse tests of electric apparatuses are calibrated by directly or indirectly comparing with a national standard. In Japan, the national-standard-class measuring system for lightning-impulse high voltage [2-6] (referred to as standard measuring system, hereafter) has been developed under Japan High-voltage Impulse testing Laboratory Liaison (JHILL). To complete the development, evaluation of uncertainty of the measurement by the standard measuring system is necessary. In this paper, uncertainty of peak-value measurements of lightning-impulse high voltage is evaluated.

2 STANDARD MEASURING SYSTEM

The standard measuring system is composed of a standard voltage divider, calibrators and a digital recorder as shown in Figure 1. The standard voltage divider is a shielded voltage divider. Its rated voltage is 500 kV. The digital recorder is a TR-AS200-14 manufactured by DR. Strauss system-elektronik GMBH. Its vertical resolution is 14 bits and its maximum sampling rate is 200MS/sec. The calibrators are designed by Nippon institute of technology and manufactured by Pulse electronics co. ltd. They output +0.84/60μs, -0.84/60μs, +1.54/60μs, or -0.84/60μs lightning-impulse voltages. Their maximum input voltage is 500V (DC).

3 EVALUATION OF UNCERTAINTY OF MEASUREMENT

3.1 Factors which cause uncertainty of measurement

The standard voltage divider and the calibrators had been used in another measuring system. Uncertainty of the peak-value measurement by that system had been evaluated [5]. In that evaluation, following items are considered.

(1) Uncertainty due to nonlinearity of the standard voltage divider.
(2) Uncertainty due to electromagnetic interference.
(3) Dispersion of DC-scale-factor measurement.
(4) Uncertainty of DC-scale-factor measurement.
(5) Uncertainty due to short-term stability of the standard voltage divider.
(6) Uncertainty due to long-term stability of the standard voltage divider.
(7) Uncertainty of the calibrators.
(8) Dispersion of measurement in the calibration test of the digital recorder.
(9) Uncertainty due to influence of the nominal epoch.
(10) Dispersion of AC-scale-factor measurement.
(11) Uncertainty due to temperature characteristics of the standard voltage divider.
(12) Uncertainty due to humidity characteristics of the standard voltage divider.

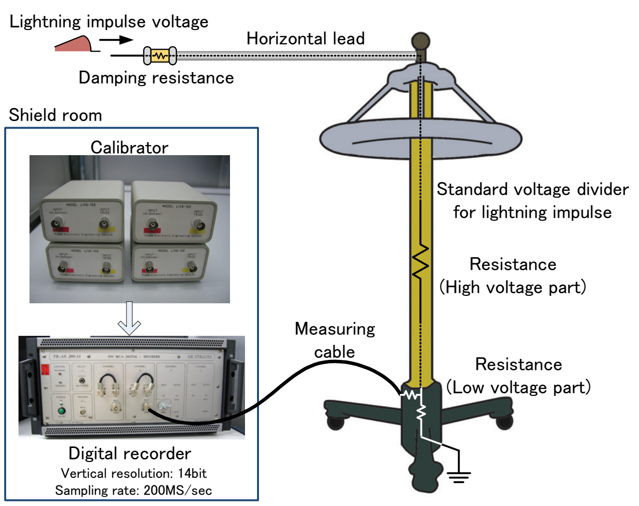

Figure 1: National-standard class measuring system for lightning impulse voltage in Japan.

In ref. [5] the uncertainty due to influence of the nominal epoch is evaluated based on a comparison with the national standard of Australia. In this paper, evaluation method which is not based on comparisons is employed. That is based on a step-response test. In this case, not the dispersion of the AC-scale factor measurement (item (10)) but that of the step-response measurement has to be evaluated. Therefore, the item (10) is replaced as follow.

(10**)** Dispersion of step-response measurement.

The uncertainties due to items (11) and (12), which are uncertainties originated from the standard voltage divider itself, are so small in the evaluation of ref. [5] that they hardly contribute to the resultant combined uncertainty. Therefore they are not re-evaluated and remaining ten items are evaluated in this paper.

3.2 Evaluation of uncertainties by each factor

3.2.1 Uncertainty due to nonlinearity of the standard voltage divider. When the scale factor is not constant within the range of the measuring voltage of the standard voltage divider, this nonlinearity causes uncertainty. In the test for the evaluation of the nonlinearity, full-lightning-impulse high voltage is injected into the standard voltage divider and its peak value, V_{imp}, is measured. The Lightning-impulse voltage is generated by an impulse generator (IG) SGD1600/80 manufactured by Haefely test AG. Its rated voltage is 1600kV and rated capacity is 80kJ. Charging voltage of one stage of the IG, V_c, is used as a reference. The charging voltage is measured by a digital multi meter 3458A manufactured by Agilent Technologies through a DC voltage divider. The number of measurements is 10 for one charging voltage. The ratios of measured V_{imp} *and* V_c are summarized in Table 1. The measured ratios in Table 1 do not show simple increase or decrease with the charging voltage. It is assumed that the ratios show simple increase or decrease due to the nonlinearity of the standard voltage divider. Table 1 exhibit not only the nonlinearity of the standard voltage divider but also that of the IG, namely, nonlinearity between the charging voltage and the peak value of the generated lightning impulse [7]. However, it can be seen that evaluation based on Table 1 including both the nonlinearity of the standard voltage divider and that of the IG is strict.

The maximum deviation of the ratio is 0.15%. Assuming that the deviations of the scale factor due to the nonlinearity of the standard voltage divider are uniformly distributed between -0.15% and +0.15%, the uncertainty due to it, u_1, is evaluated as follow.

$$u_1 = \frac{0.15}{\sqrt{3}} = 0.09 \ \ \% \qquad (1)$$

3.2.2 Uncertainty due to electromagnetic interference. Electromagnetic fields associated with high-voltage impulse may induce voltage on the standard voltage divider. This causes uncertainty of the measurement. The electromagnetic-interference-voltage waveform generated when a full lightning-impulse voltage of 500kV in amplitude is injected to the standard voltage divider is measured 10 times by shorting its low voltage part. The injected voltage is measured simultaneously by using a reference voltage divider. An example of the injected lightning-impulse-voltage waveform and the interference-voltage waveform are shown in Figure 2. The average ratio of the peak values of the interference voltages to those of the injected voltages is 0.03% for the positive lightning impulses and 0.03% for the negative impulses. Note that the polarities of the interference voltages are the same as the injected voltages. Assuming that the peak values of the interference voltages are uniformly distributed between 0.00% and +0.03% of the peak value of the injected lightning impulses, the uncertainty due to electromagnetic interference, u_2, is evaluated as follow.

Table 1: Result of linearity test.

Charging voltage	positive		Negative	
	V_{imp}/V_c	Deviation from average	V_{imp}/V_c	Deviation from average
200kV	14.768	0.15%	14.793	-0.02%
280kV	14.800	-0.07%	14.796	-0.09%
360kV	14.796	-0.03%	14.788	0.02%
440kV	14.798	-0.05%	14.798	-0.05%
520kV	14.769	0.14%	14.789	0.01%
Average of V_{imp}/V_c	14.790			

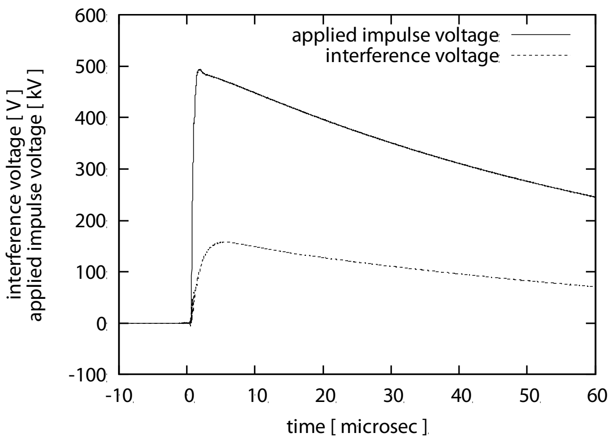

Figure 2: Example of measured interfering voltage waveform.

$$u_2 = \frac{0.03}{2\sqrt{3}} = 0.01\% \tag{2}$$

3.2.3 Dispersion of DC-scale-factor measurement. Dispersion of DC-scale-factor measurement causes the uncertainty of the measurement. In the DC-scale-factor measurement, DC voltage generated by R6161 manufactured by Advantest Corporation is injected to the standard voltage divider and the output/input ratio is measured 10 times by a digital multi meter 3458A manufactured by Agilent Technologies. The measured DC scale factors are summarized in Table 2.

Uncertainty due to a dispersion of measurements, u_A, can be evaluated by using eq. (3).

$$u_A = \frac{\kappa\sigma}{2\sqrt{n}} \tag{3}$$

Where σ is a standard deviation of measurements, n is the number of measurements, and κ is a coefficient determined from the Student's t-distribution table. When n is 10 and confidential level is 95%, κ is 2.262.

The uncertainty due to the dispersion of the DC-scale-factor measurement, u_3, can be evaluated using eq. (3) by rounding to the second decimal as follow.

$$u_3 = \frac{\kappa\sigma}{2\sqrt{n}} = 0.00\% \tag{4}$$

3.2.4 Uncertainty of DC-scale-factor measurement. Uncertainty of the calibration of the measuring device employed in DC-scale-factor measurements causes the uncertainty. When the input voltage to the standard voltage divider, V_H, is 100V, the output voltage, V_L, is 0.10489V as the scale factor is 953.51. The uncertainty of the calibration of the measuring device is 3ppm with the coverage factor, k, of 2 for both the 100V and the 1V range. The standard deviations due to this uncertainty in the DC voltage measurement in the100V range, σ_{100V}, and in the 1V range, σ_{1V}, are followings.

$$\sigma_{100V} = \frac{3\times10^{-6}}{2}\times100 = 1.500\times10^{-4}\ \ V \tag{5}$$

$$\sigma_{1V} = \frac{3\times10^{-6}}{2}\times0.1049 = 1.573\times10^{-7}\ \ V \tag{6}$$

Standard deviation of the DC-scale-factor measurement due to the uncertainty of the calibration of the measuring device, σ_{SF}, is calculated by following equation.

$$\sigma_{SF}{}^2 = \left[\frac{\partial(V_H/V_L)}{\partial V_H}\right]^2 \sigma_{100V}{}^2 + \left[\frac{\partial(V_H/V_L)}{\partial V_L}\right]^2 \sigma_{1V}{}^2 = \left(\frac{1}{V_L}\right)^2 \sigma_{100V}{}^2 + \left(-\frac{V_H}{V_L{}^2}\right)^2 \sigma_{1V}{}^2 \tag{7}$$

$$\sigma_{SF} = 0.002023 \tag{8}$$

Uncertainty due to the calibration of the measuring device used for DC-scale-factor measurements, u_4, is evaluated by rounding to the second decimal as follow.

$$u_4 = \frac{0.002023}{953.51}\times100 = 0.00\ \ \% \tag{9}$$

Note that, generally, a calibration value is valid at the point of the calibration. Therefore, the employed uncertainties due to the calibration of the measuring device in this paper are not valid. However, the evaluated uncertainty is too small. Therefore, it can be seen that the annual variation of the measuring devices hardly affects the resultant uncertainty of the peak value measurements.

3.2.5 Uncertainty due to short-term stability of the standard voltage divider. Variation of the DC scale factor after the injection of lightning-impulse high voltage causes the uncertainty. After the DC-scale-factor measurement of Table 2, full lightning-impulse voltage of 500kV in amplitude is injected to the standard voltage divider 20 times. After that, the DC scale factor is measured 10 times immediately. The injection frequency is the maximum frequency of the standard voltage divider (1time/30sec) and the number of the injections, 20 times, is determined from the number of the injection in a calibration test. The measured DC scale factor is summarized in Table 3.

Table 2: Measured DC scale factor before injection of 500 kV full lightning impulse to the standard voltage divider.

Input voltage	＋100V	－100V
DC scale factor (average)	953.329	953.292
Standard deviation	0.0002%	0.0003%
Average of positive and negative	953.310	

Table 3: DC scale factor measured after 20 times injection of 500 kV full lightning impulse to the standard voltage divider.

Input voltage	＋100V	－100V
DC scale factor（average）	953.336	953.372
Average of positive and negative	953.354	

In principle, uncertainty due to the short-term stability should be evaluated by repeating the above-mentioned test. However, the injection interval of actual calibration tests is much longer than this test because it is determined concerning stability of generation of impulse voltage. Therefore, it can be seen that the evaluation based on this test is strict.

The variation of the DC scale factor measured before and after the injection of the lightning-impulse high voltage is 0.00%. Therefore, the uncertainty due to the short-term stability, u_5, is evaluated to be 0.00%.

3.2.6 Uncertainty due to long-term stability of the standard voltage divider. Annual variation of the DC scale factor causes the uncertainty. The annual variation is summarized in Table 4. The maximum deviation of the measured DC scale factor from the average is 0.02%. Assuming that the annual variations of the DC scale factor are uniformly distributed between -0.02% and +0.02%, the uncertainty due to the long-term stability, u_6, is evaluated as follow.

$$u_6 = \frac{0.02}{\sqrt{3}} = 0.01 \quad [\%] \tag{10}$$

3.2.7 Uncertainty of the calibrators. The peak value of the low voltage lightning impulse generated by the calibrators is determined by a circuit simulation. The circuit elements of the calibrators are measured with disconnecting them from the circuit and they are employed in the simulation. A digital multi meter WaveTek1281 manufactured by Yokogawa Electric Corporation is employed for the resistance measurement and an LCR meter 7600 manufactured by QuadTech is employed for the capacitance measurement. The measurement frequency is 100kHz.

Table 4: Annual variation of DC scale factor.

Date	DC scale factor	Deviation from average
1999/12	953.56	0.02%
2001/10	953.49	0.01%
2002/09	953.25	-0.01%
2003/12	953.44	0.01%
2004/12	953.31	-0.01%
2005/12	953.31	-0.01%
2006/10	953.31	-0.01%
2007/04	953.26	-0.01%
2007/12	953.56	0.02%
2008/11	953.23	-0.02%
Average	953.37	———
Maximum of deviation	———	0.020%

Uncertainties of the element measurements cause the uncertainty. The uncertainty of the element measurements can be evaluated by uncertainty of the calibration of the measuring devices. Varying element values with the value of the uncertainty of the element measurement, circuit simulations are carried out. The variation of the peak value is summarized in Table 5. The uncertainty of the calibrator due to the uncertainty of the element measurement is a root mean square of them. The uncertainty of the calibrators for 0.84/60μs or 1.56/60 μs lightning-impulse voltages, u_7, is evaluated to be 0.07%.

3.2.8 Dispersion of measurement in the calibration test of the digital recorder. The digital recorder of the standard measuring system is calibrated by measuring the low voltage lightning impulses generated by the calibrators. Dispersion of the measured peak values causes the uncertainty. In the calibration test of the digital recorder, the standard deviation of the 10 times measurement is 0.02%. From eq. (3) the uncertainty due to the dispersion of the measurements in the calibration test of the digital recorder, u_8, is evaluated as follow.

$$u_8 = \frac{\kappa\sigma}{2\sqrt{n}} = 0.01 \quad \% \tag{11}$$

3.2.9 Uncertainty due to influence of the nominal epoch. Front time of lightning impulse waveforms to be measured by the standard measuring system is ranging from 0.84μs to 1.56 μs. When the scale factor is not constant in this range of the front time, it causes the uncertainty.

To evaluate this uncertainty step response tests [6] are carried out. In the test, 10 step-response waveforms are measured. Representing 0.84/50 μs, 1.20/50 μs, and 1.56/50μs lightning-impulse-voltage waveforms as inputs to the standard voltage divider using so-called double-exponential function, output waveforms are calculated by convolution algorithm with the measured step-response waveforms. Table 6 summarizes deviation of the front time between the

Table 5: Uncertainty of peak value of calibrator output due to uncertainty of elements measurement.

	R_c	R_s	R_0	C	C_0	R_{dr}	C_{dr}	L	Uncertainty
+0.84/60μs, −0.84/60μs	0.00%	0.00%	0.00%	0.04%	0.03%	0.00%	0.05%	0.00%	0.07%
+1.56/60μs, −1.56/60μs	0.00%	0.00%	0.00%	0.04%	0.04%	0.00%	0.05%	0.00%	0.07%

Table 6: Deviation of front time between input and the output waveforms calculated based on step-response waveforms.

	0.84/50μs	1.20/50μs	1.56/50μs
average	0.02%	0.08%	0.12%
Standard deviation	0.00%	0.00%	0.00%

Table 7: Evaluation of uncertainty of peak-value measurement of lightning impulse voltage by the standard measuring system.

	Items	Value
u_1	Nonlinearity of the standard voltage divider	0.09%
u_2	Electromagnetic interference	0.01%
u_3	Dispersion of DC scale factor	0.00%
u_4	Uncertainty of DC-scale-factor measurement	0.00%
u_5	Short-term stability of the standard voltage divider	0.00%
u_6	Long-term stability of the standard voltage divider	0.01%
u_7	Uncertainty of the calibrator	0.07%
u_8	Dispersion of recorder calibration	0.01%
u_9	Influence of nominal epoch	0.03%
u_{10}	Dispersion of step-response measurement	0.00%
u_c	combined standard uncertainty	0.12%
U	Expanded uncertainty（coverage factor k=2）	0.3%

Table 8: Uncertainty of peak value measurement of lightning impulse voltage by national standard of other major countries [8].

Country	Organization	Uncertainty
Germany	PTB： Physikalisch-TechnischeBundesanstalt	0.4%
Finland	HUT： Helsinki University of Technology	0.5%
Australia	NMI： National Measurement Institute	0.4%

input and the output waveforms. Assuming that the deviations of the peak value are uniformly distributed between 0.00% and 0.12% for the front time from 0.84 μs to 1.54 μs, the uncertainty due to the influence of the nominal epoch, u_9, is evaluated as follow.

$$u_9 = \frac{0.12}{2\sqrt{3}} = 0.03 \quad \% \tag{12}$$

3.2.9 Dispersion of step-response measurement. Dispersion of the step-response measurement causes the uncertainty. In Table 6, the maximum standard deviation is 0.00%. Therefore, the uncertainty due to dispersion of the step-response measurement, u_{10}, is evaluated to be 0.00%.

3.3 Combination of factors which cause uncertainty of peak-value measurement.

The factors which cause the uncertainty, evaluated above, are summarized in Table 7. The combined uncertainty of them, u_c, is calculated by eq. (13).

$$u_c = \sqrt{\sum_i u_i^2} \tag{13}$$

The combined uncertainty of the peak value measurements is evaluated to be 0.12%. The expanded uncertainty with the coverage factor, k, of 2 is evaluated to be 0.3 by rounding up to the first decimal.

4 DISCUSSION

The uncertainty of the peak value measurement required for a national standard is not specified in IEC60060-2 [1] and that required for a reference measuring system is 1%. The evaluation result in this paper is less than 1/3 of the requirement for a reference measuring system.

Table 8 summarizes uncertainties of the peak value measurement by national standard of major countries [8]. The uncertainty of the peak value measurement by the standard measuring system evaluated in this paper is the smallest level in the world.

In the data base of BIPM (International Bureau of Weights and Measures) [8], only the uncertainty values of measurements by national standards are published. Evaluation method of the uncertainty of the peak value measurement by German national standard is published in ref. [9]. Not that ref. [9] is published in 1989, therefore, current evaluation of German system would be updated.

The factors evaluated in ref. [9] are summarized in Table 9. The nonlinearity of the voltage divider contributes to the resultant uncertainty the most and the other factors hardly contribute. On the other hand, in the case of the standard measuring system evaluated in this paper, contributions of nonlinearity of the standard voltage divider and the uncertainty of the calibrators are large. The other factors hardly contribute. Note that in the evaluation in ref. [9], the uncertainty of calibrators is not taken into account. In this paper, the uncertainty due to A/D conversion and inherent self-noise of the digital recorder is not taken into account. However, it can be seen that it hardly contributes to the result of the uncertainty evaluation because vertical resolution of the digital recorder of the standard measuring system is 14 bits whereas that of ref. [9] is 12 bits.

Table 9: Evaluation of uncertainty of peak value measurement of lightning impulse voltage by German standard measuring system. [9]

	factors	value
u_1	Long-term stability of voltage divider	0.06%
u_2	Nonlinearity of voltage divider	0.12%
u_3	Temperature characteristics of voltage divider	0.03%
u_4	Humidity characteristics of voltage divider	0.04%
u_5	A/D conversion and inherent self-noise of recorder	0.03%
u_6	Electromagnetic interference	0.03%
u_c	combined standard uncertainty	0.14%
U	Expanded uncertainty（coverage factor k=2）	0.3%

5 CONCLUSION

In this paper, the uncertainty of the peak-value measurement of lightning-impulse high-voltage by the standard measuring system is evaluated. The evaluated uncertainty is 0.3% with the coverage factor, *k*, of 2. This is less than the 1/3 of the requirement for a reference measuring system and is the smallest level in the world.

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