

2-3 Calibration of Standard Voltage and Current Generator

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This paper describes the calibration method of standard voltage and current generators that provide a reference voltage/current in order to calibrate testers (analogue multi-meters) and digital multi-meters (DMM). A Standard voltage/current generator can generate very precise DC voltage, DC current, AC Voltage, or AC current. Since the frequency range of the output signal of such a generator is from DC up to 400 Hz, it is necessary to perform the measurement operation with special care that is different from that in an RF band. In this paper, the calibration procedure of the generator and evaluation of the calibration uncertainties are described.

1 Introduction

A standard voltage and current generator is a signal source that can precisely generate the desired DC or AC voltage and current for use in calibrating voltage and current meters called “testers” and “multi-meters.” The frequencies of AC voltage and current include 50 Hz and 60 Hz, which are commercial power supply frequencies and 400 Hz for use in passenger aircraft.

The Radio Law requires the use of a calibrated voltammeter when testing wireless equipment. NICT provides calibration services for radio frequency measurement instruments, such as high frequency power meters, attenuators, and antennas. NICT also provides calibration services for DC/low frequency measurement devices that are voltmeters and standard voltage and current generators, as some of the devices for testing wireless equipment.

As a laboratory accredited under the Japan Calibration Service System (JSCC), NICT has also provided calibration services that satisfy the ISO/IEC17025 standard, for standard voltage and current generators, since 2006.

This paper describes the calibration of voltage and current of DC/low frequency ranges, while showing actual calibration procedures. It also describes how to estimate uncertainty associated with calibration results.

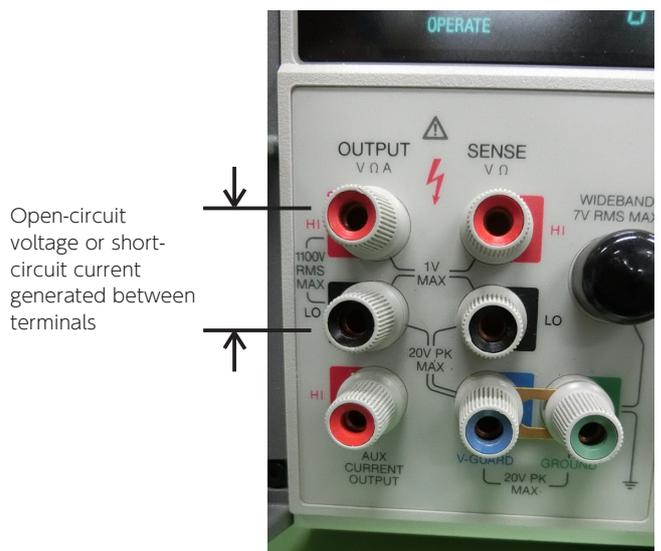
2 Definitions

The calibration of the voltage and current of a standard voltage and current generator is carried out for the purpose of ascertaining the open-circuit voltage and short-circuit current at the output terminal pair shown in Fig. 1 (b), for

the voltage value and current value set in a standard voltage and current generator shown in Fig. 1 (a). In practice,



(a)



(b)

Fig. 1 Standard voltage and current generator and calibration reference plane

as shown in Fig. 2, calibration is done by connecting a digital multi-meter and taking measurements.

3 Calibration method

The calibration of a standard voltage and current generator, as shown in Fig. 2, is performed by the substitution method, which uses a digital multi-meter (hereinafter,

“DMM”) to measure and compare output from a reference standard device maintained and managed by NICT (hereinafter, “standard device”), and output from a standard voltage and current generator being calibrated (hereinafter, “device under test”) [1]. The DMM used for the comparison must be sufficiently precise to enable the discovery of differences between the voltage and current generated from a standard voltage and current generator, and must have linearity in the range of those differences. Also, voltage measurement terminals must have sufficiently large internal resistance, and current measurement terminals must have sufficiently small internal resistance. One must also be careful about the material quality and length of the cables that connect the standard voltage and current generator to the DMM. The effects of these are assessed as sources of uncertainty of calibration results, as described later.

The specific procedures are as follows. Figure 3 shows an outline of the procedures.

- (1) Connect the device under test to the DMM, set the indicated value of the device under test to the nominal value $V_{NOMINAL}$, and read the V_{DUT} value displayed on the DMM when output.
- (2) Connect the standard device to the DMM, set the indicated value of the standard device to the nominal



Fig. 2 Calibration of standard voltage and current generator (Top) Multi-meter: Fluke 8508A, (Middle) Amplifier: Fluke 5725A (Bottom) Standard voltage and current generator: Fluke 5720A

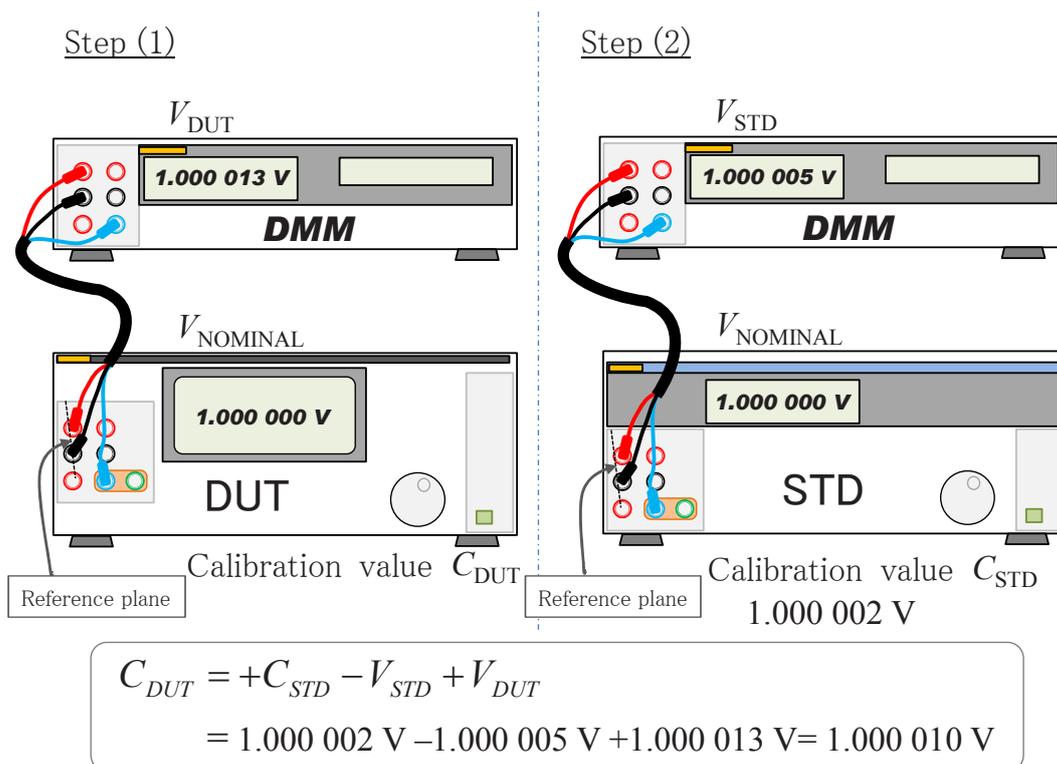


Fig. 3 Calibration procedure

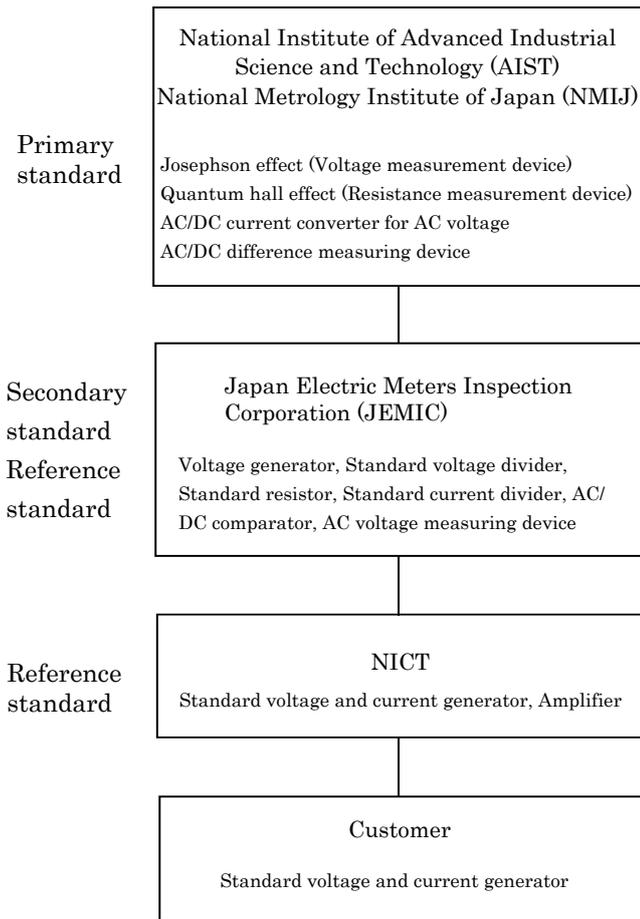


Fig. 4 Traceability chart

value V_{NOMINAL} , and read the V_{STD} value displayed on the DMM when output.

- (3) Use the following equation to determine the calibration value C_{DUT} for the indicated value V_{NOMINAL} of the device under test. (For derivation of the equation, see the Appendix.)

$$C_{\text{DUT}} = +C_{\text{STD}} - V_{\text{STD}} + V_{\text{DUT}} \quad (1)$$

Here, C_{STD} is the calibration value for the indicated value V_{NOMINAL} , obtained when the upper-level calibration organization calibrated the standard device.

In actual calibration work, values measured multiple times by a DMM are read on a PC connected to the DMM, and the average value and experimental standard deviation are recorded.

Also, for the calibration value C_{STD} of the standard device, the value calibrated at the superior calibration organization is used. NICT ensures traceability to the national standard by the traceability system shown in Fig. 4.

Table 1 Calibration items at NICT

Item	Frequency	Voltage, Current
DC voltage	DC	1 V, 10 V, 100 V
DC current	DC	10 mA, 100 mA, 1 A, 10 A
AC voltage	50 Hz, 60 Hz, 400 Hz	10 V, 100 V
AC current	50 Hz, 60 Hz	100 mA, 1 A, 10 A

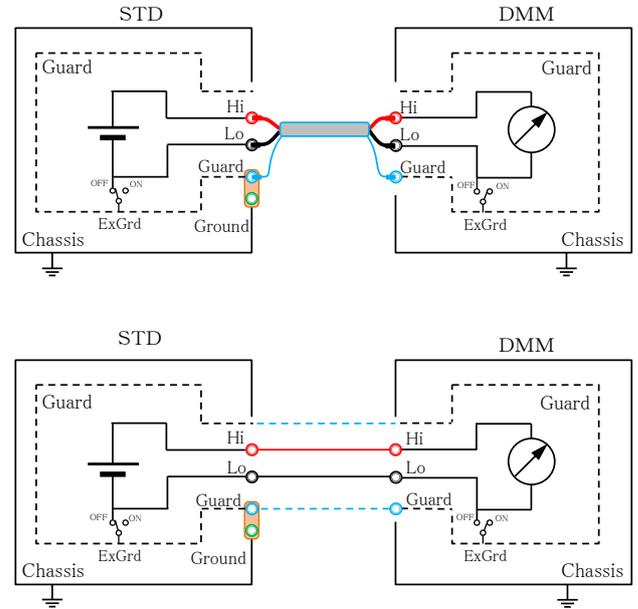


Fig. 5 Shielding and grounding

4 Calibration results

4.1 Standard device and DMM

Table 1 shows voltage and current calibration performed by NICT as a JCSS-accredited laboratory. For the standard device, a Fluke 5720A Multifunction Calibrator is used. Within the calibration range shown in Table 1, for 10 A DC current and 10 A AC current, a dedicated Fluke 5725A Amplifier is used to generate current. Japan Electric Meters Inspection Corporation (JEMIC) performs calibrations for these once per year, and obtains the calibration value C_{STD} . On the other hand, the Fluke 8508A Reference Multimeter is used as the DMM to compare outputs of the standard device vs. the device under test (Fig. 2).

4.2 Connection method

When connecting a standard voltage and current generator to a DMM, ground one of the measurement terminals to enable stable measurements. As shown in Fig. 1 (b), the standard device 5720A has output terminals (Hi, Lo), guard terminal and ground terminal. Also, the DMM 8508A has an input terminal and a guard terminal. The

standard voltage and current generator and DMM are connected by two lead wires shielded by wire mesh, and the wire mesh part is connected to both guard terminals. That is, the standard voltage and current generator and DMM are measured inside the metal shielding called “guards,” represented by the dashed lines in Fig. 5 [2][3].

Here, stable measurements are achieved by conducting between the Lo terminal and guard terminal. The standard

device and DMM have a button labeled [Ex Grd] (External Guard), which turns on/off the conduction between the Lo terminal and guard in the unit. If this button is on, it cuts the conduction between the Lo terminal and guard. When it is off, there is conduction between the Lo terminal and

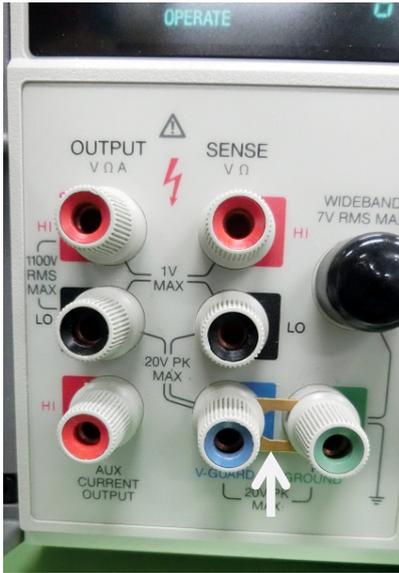


Fig. 6 Short-circuit plate

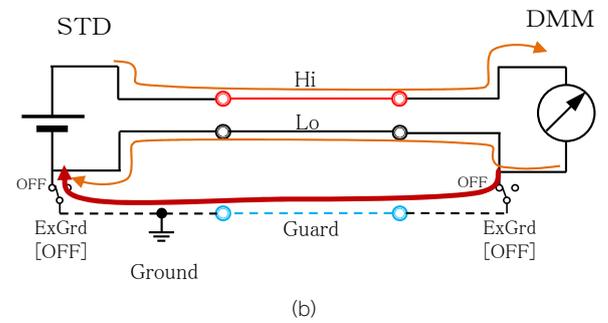
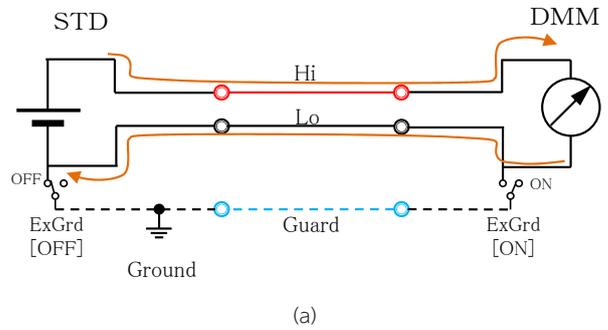


Fig. 7 Generation of unwanted current pathway

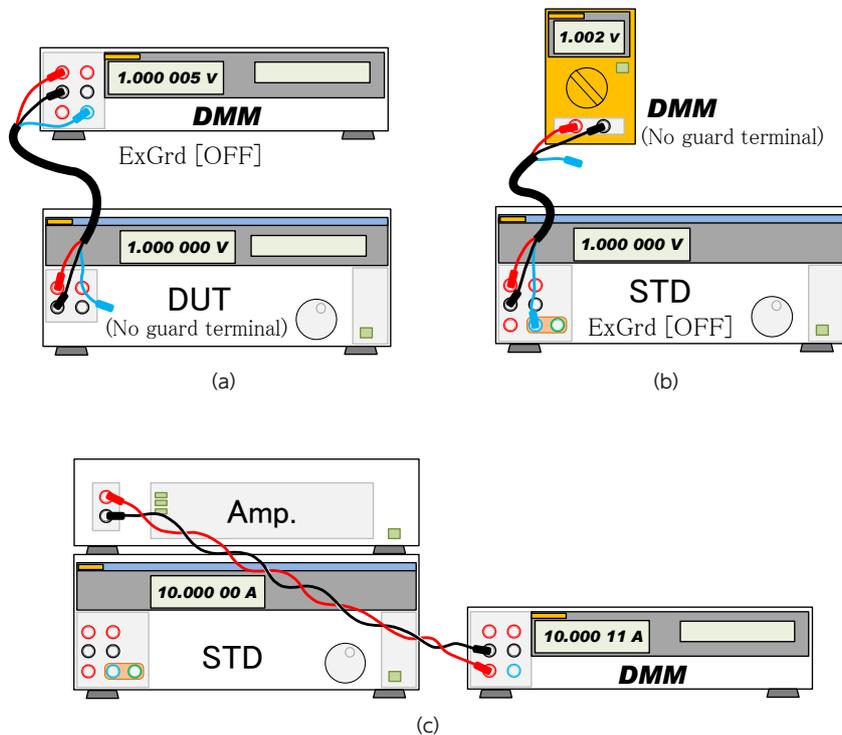


Fig. 8 External guard settings example

(a) If calibrating a standard device that has no guard terminal, (b) If calibrating a DMM that has no guard terminal, (c) If using an amplifier

guard. Moreover, as shown in Fig. 6, the standard device has a short plate (short circuit plate) for conductivity between the external guard terminal and ground terminal. The ground terminal conducts with the case. The short plate can be removed.

Here, as shown in Fig. 7 (a), the guard must be con-

nected with only one Lo terminal on either the standard device or DMM. This is a method called “Single-point earth.” If as shown in Fig. 7 (b), the guard conducts with the Lo terminals on both standard device and DMM, then unwanted current flows via the guard, so correct measurements cannot be taken.

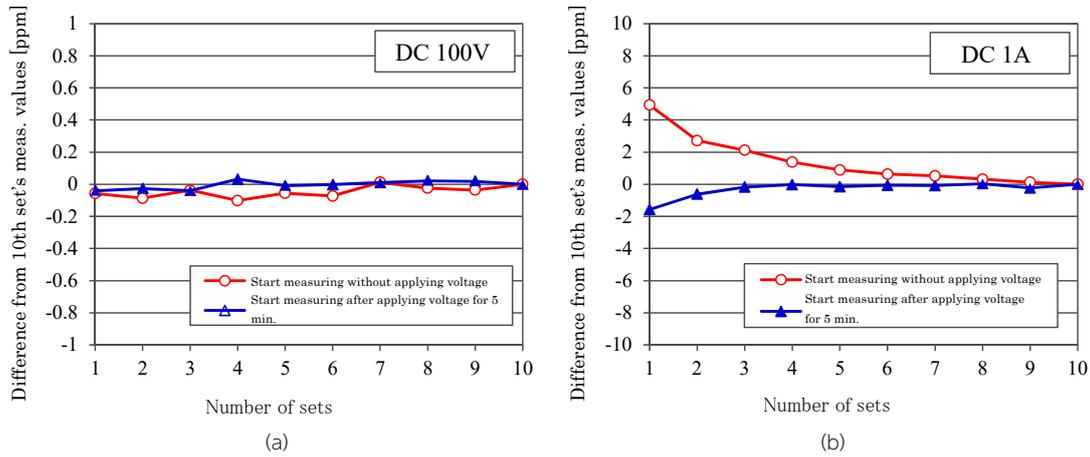


Fig. 9 Number of measurement sets until measurement values converge
(Combination of standard device and DMM)

Table 2 Example of calibration results
Device under test: Fluke 5700A

Calibration item			Calibration value of standard device C_{STD} ①	Measured value of standard device V_{STD} ②	Measured value of DUT V_{DUT} ③	Calibration result C_{DUT} ① - ② + ③
DC voltage	1 V	—	1.000 000 3 V	1.000 002 6 V	1.000 002 3 V	1.000 000 0 V
	10 V	—	10.000 000 V	10.000 015 V	10.000 020 V	10.000 005 V
	100 V	—	99.999 91 V	100.000 02 V	100.000 14 V	100.000 03 V
DC current	10 mA	—	9.999 97 mA	10.000 01 mA	9.999 99 mA	9.999 95 mA
	100 mA	—	100.000 3 mA	100.001 4 mA	100.001 0 mA	99.999 9 mA
	1 A	—	1.000 010 A	1.000 070 A	1.000 067 A	1.000 007 A
	10 A	—	10.001 49 A	10.001 75 A	10.001 65 A	10.001 39 A
AC voltage	10 V	50 Hz	10.000 07 V	9.999 30 V	9.999 33 V	10.000 10 V
		60 Hz	10.000 04 V	9.999 45 V	9.999 46 V	10.000 05 V
		400 Hz	10.000 00 V	9.999 76 V	9.999 77 V	10.000 01 V
	100 V	50 Hz	99.999 2 V	99.992 3 V	99.995 0 V	100.001 9 V
		60 Hz	99.999 6 V	99.993 6 V	99.996 3 V	100.002 3 V
		400 Hz	99.999 4 V	99.996 8 V	99.999 5 V	100.002 1 V
AC current	100 mA	50 Hz	100.005 mA	99.989 mA	99.989 mA	100.005 mA
		60 Hz	100.006 mA	99.992 mA	99.992 mA	100.006 mA
	1 A	50 Hz	1.000 07 A	0.999 87 A	0.999 88 A	1.000 08 A
		60 Hz	1.000 08 A	0.999 91 A	0.999 91 A	1.000 08 A
	10 A	50 Hz	10.002 5 A	10.000 3 A	10.000 3 A	10.002 5 A
		60 Hz	10.002 6 A	10.000 6 A	10.000 6 A	10.002 6 A

The device under test determines whether grounding is performed on the standard voltage and current generator side, or on the DMM side. As a reference, Fig. 8 (a) shows a wiring diagram used if calibrating a standard voltage and current generator that does not have a guard terminal, whereas Fig. 8 (b) shows a wiring diagram if calibrating a DMM or tester that does not have a guard terminal. Moreover, if an amplifier is used, the amplifier does not have a guard terminal, so as shown in Fig. 8 (c), the instruction manual [3] recommends that 2 lead lines connect the amplifier to the DMM, but magnetic fields arriving from outside are captured in the loop created by the 2 lead lines and devices, so it is recommended to twist the 2 lead lines to prevent bad effects on measurement results. As described above, depending on the device under test, consider the grounding method, then perform measurements.

4.3 Necessity of applying a current before measuring

To achieve stable measurements, we studied the necessity of applying a voltage or current to the DMM before starting measurements. The two graphs in Fig. 9 show results when we connected the standard device and DMM, and applied DC 100 V or DC 1 A. The measurements were done 100 times as 1 set, with a 1 minute rest period between sets; we measured 10 sets. The graph’s vertical axis shows deviations of measurement values from sets 1 to 9, when the 10th set’s measurement results are a reference (unit is ppm).

In the figure, the red ○ and lines show the results of 10 sets of measurements when the first measurements are started after letting the devices reach room temperature (23 °C±2 °C). The blue ▲ and lines show the results of 10 sets of measurements performed by activating the standard device and DMM and applying a voltage or current for 5 minutes, before starting the first set of measurements.

In Figure 9 (b), looking at the graph’s red ○ and line, multiple sets of measurements are required until the measurement values converge to a certain value. Looking at the graph’s blue ▲ and line, a current was continually applied for 5 minutes, which made the measurement values converge earlier. On the other hand, in the case of voltage measurements shown in Fig. 9 (a), we see there is sufficient convergence. From these results, it seems that DC measurements take time to converge on a certain value because during current measurements, a resistance temperature rise in the DMM causes change in the value of resistance. When

measuring a large current, more heat is generated from resistance in the DMM, so special care is needed.

4.4 Calibration results

We show the results of calibrating a Fluke 5700A Multifunction Calibrator as the device under test. Similar to the standard device, the 5700A has a guard terminal and ground terminal, but we performed calibration with a short circuit plate connected between both terminals, assuming that the customer requests such a condition for calibration.

In this case, the Lo terminal and guard terminal are connected on the device under test and standard device, so one must cut the connection between the guard and ground on the DMM side. Therefore, we turned ON the DMM’s [Ex Grd] button, then performed measurements. Table 2 shows the calibration results. The number of digits of calibration results depends on the uncertainty described below: DC voltage 7 digits, DC current 6 digits, AC voltage 6 digits, AC current 5 digits. If DC or AC 10 A current using an amplifier, then there is large uncertainty of output from the amplifier, so even if displayed on the DMM, the number of digits decreases for final results.

5 Uncertainty

Uncertainty associated with calibration results is displayed as expanded uncertainty estimated to have an approximately 95 % confidence level. The size of that value which occurs due to multiple sources as described below can be estimated by using the following equation to compose it [1][4].

$$u(C_{DUT}) = \sqrt{u(C_{STD})^2 + u(V_{STD})^2 + u(V_{DUT})^2 + s^2} \tag{2}$$

- Here,
- $u(C_{DUT})$: Uncertainty of device under test.
- $u(C_{STD})$: Uncertainty of standard device.
- $u(V_{STD})$: Uncertainty of the measurement value displayed on the DMM, when the indicated value of the standard device is aligned with $V_{NOMINAL}$, and voltage and current are output.
- $u(V_{DUT})$: Uncertainty of the measurement value displayed on the DMM, when the indicated value of the device under test is aligned with $V_{NOMINAL}$, and voltage and current are output.
- s : Variability of calibration results.

Each item is explained below.

5.1 $u(C_{\text{STD}})$: Uncertainty of standard device.

5.1.1 Uncertainty of calibration at a superior calibration organization

As shown in Fig. 4, the standard devices maintained and managed by NICT are calibrated by the Japan Electric Meters Inspection Corporation (JEMIC). NICT calibrates with reference to the calibration values and uncertainty written in the calibration certificates issued by JEMIC.

It is written in a calibration certificate that the expanded uncertainty reported in the calibration certificate is stated as the standard uncertainty multiplied by a coverage factor $k=2$, providing a level of confidence of approximately 95 %. Therefore, standard uncertainty is the value of uncertainty written in the calibration certificate, divided by the coverage factor $k=2$.

5.1.2 Performance of standard device

Calibration of a standard device is done once per year, but its characteristics can change while that year passes. The degree of that change over time is written as uncertainty in the instruction manual, and as long as it is not damaged, the change in output over the year falls within the range of that uncertainty. In other words, this shows that even if not damaged, output can change within the range of that uncertainty. In the extended specification document of the Fluke 5720A standard device, uncertainty in 1 year is written as a value with a 99 % confidence level, so divide it by the coverage factor $k=2.576$ to obtain the standard uncertainty.

5.2 $u(V_{\text{STD}})$: Uncertainty of measurement results of standard device

When the standard device is connected to a DMM and measured, the V_{STD} value obtained can be considered to have uncertainty that depends on the following sources.

5.2.1 Performance of DMM

For uncertainty of performance of the DMM that measures voltage and current output from the standard device or device under test, the linearity and degree of stability etc. of the measurement device are expected to affect calibration results. However, since it takes little time to perform measurements by replacing the standard device with the device under test, the DMM can be considered to be sufficiently stable, and tiny differences in output from the standard device or device under test near the indicated value V_{NOMINAL} are measured within a range where the linearity of DMM is sufficiently sustained, so uncertainty caused by the DMM's performance is assumed to be 0. Fluctuations of measured values during the measurement

period are included in “variability” described later.

5.2.2 Resolution of digital indication of DMM

One cannot know the values of digits beyond the minimum number of digits displayed on the DMM, so they are considered uncertain. Now, considering when the measurement result is displayed as 0.98 V, then as shown in Fig. 10, if values were measured in the range from 0.975 to 0.985 V ($0.98 \text{ V} \pm 0.005 \text{ V}$), all are displayed as 0.98 V. That is, values of the third and digits further below the decimal point are uncertain, and the true measured value could exist anywhere, so the probability density distribution is considered uniform, and the standard uncertainty is obtained. In the case of the above example, standard uncertainty is $0.0029 \text{ V} (= 0.005 / \sqrt{3} \text{ V})$.

5.2.3 Effects of thermoelectromotive force (Only when measuring DC voltage)

A cable is used to connect the DMM to the standard voltage and current generator, but when terminals of different metals are connected, and there are temperature differences between the 4 terminals, we see that thermoelectromotive force occurs due to the Seebeck effect [5]. This phenomenon is not a problem when measuring DC current, AC voltage or AC current, but it becomes a problem when calibrating DC voltage. It especially cannot be ignored when measuring small DC voltages of 1V or less.

When measuring DC voltage, one must not only pay attention to the surrounding temperature; it is also necessary to measure the terminal temperatures while the DMM and standard voltage and current generator are connected by a lead line, and make sure that those differences are within $\pm 1.5 \text{ }^\circ\text{C}$. As conditions for measuring the size of standard uncertainty, connection points of the standard device and test lead are made of tellurium copper, and we see from the product specifications [6] that the thermoelectromotive force coefficient is $1.3 \text{ } \mu\text{V}/^\circ\text{C}$ or less. Now, if one performs measurement after checking that the temperature differences are within $\pm 1.5 \text{ }^\circ\text{C}$, then the standard uncertainty of temperature is a uniform distribution with

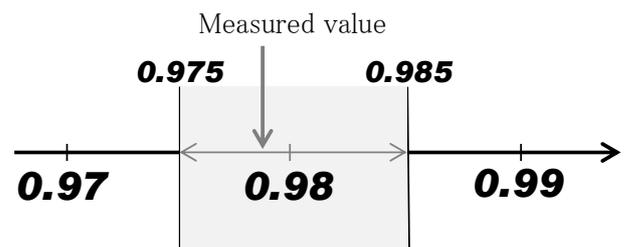


Fig. 10 Uncertainty of resolution of digital indication

Table 3 Uncertainty budget

DC Voltage: 1 V

Source ①	Distribution	Divisor ②	Value ③=①÷②	Sensitivity coefficient ④	Contribution ③×④	Note		
<i>Uncertainty of Reference Standard Device</i>								
1	Superior calibration value	3 ppm	Normal (k=2)	2	1.5 ppm	1.5 μV		
2	Spec. of Reference Standard	6.8 μV	Normal (k=2.576)	2.576	2.64 μV	2.64 μV		
<i>Uncertainty Caused by Comparative Measurement</i>								
3	Spec. of DMM	0 μV	Rectangle	√3	0 μV	0 μV	Fast mode, 7.5 digits	
<i>Uncertainty When Measuring Reference Standard Device</i>								
4	DMM Resolution	0.05 μV	Rectangle	√3	0.029 μV	0.029 μV	7.5 digits	
5	Thermoelectromotive Force	1.5 °C	Rectangle	√3	0.866 °C	1.3 μV/°C	1.13 μV	Within 3 °C (Within ± 1.5 °C)
6	Burden voltage							
<i>Uncertainty When Measuring Device Under Test</i>								
7	DMM Resolution	0.05 μV	Rectangle	√3	0.029 μV	0.029 μV	7.5 digits	
8	Thermoelectromotive Force	1.5 °C	Rectangle	√3	0.866 °C	1.3 μV/°C	1.13 μV	Within 3 °C (Within ± 1.5 °C)
9	Burden voltage							
<i>Uncertainty due to Other Sources</i>								
10	Repeatability	0.085 μV	Normal	√10	0.027 μV	0.027 μV	Measure 10 times	
Combined Standard Uncertainty					3.43 μV			
Expanded Uncertainty (Level of Confidence of approx. 95 %)					6.9 μV		Calculated with k=2	

Table 4 Uncertainty budget

DC Current: 1 A

Source ①	Distribution	Divisor ②	Value ③=①÷②	Sensitivity coefficient ④	Contribution ③×④	Note	
<i>Uncertainty of Reference Standard Device</i>							
1	Superior calibration value	6 μA	Normal (k=2)	2	3 μA	3 μA	
2	Spec. of Reference Standard	105 μA	Normal (k=2)	2.576	40.8 μA	40.8 μA	
<i>Uncertainty Caused by Comparative Measurement</i>							
3	Spec. of DMM	0 μA	Rectangle	√3	0 μA	0 μA	Normal mode, 6.5 digits
<i>Uncertainty When Measuring Reference Standard Device</i>							
4	DMM Resolution	0.5 μA	Rectangle	√3	0.289 μA	0.29 μA	6.5 digits
5	Thermoelectromotive Force						
6	Burden voltage	0.3 V	Rectangle	√3	0.173 V	0 μA	(Input impedance)×(Current value) less than 0.5V, so can be ignored
<i>Uncertainty When Measuring Device Under Test</i>							
7	DMM Resolution	0.5 μA	Rectangle	√3	0.289 μA	0.29 μA	6.5 digits
8	Thermoelectromotive Force						
9	Burden voltage	0.3 V	Rectangle	√3	0.173 V	0 μA	(Input impedance)×(Current value)
<i>Uncertainty due to Other Sources</i>							
10	Repeatability	1.98 μA	Normal	√10	0.626 μA	0.63 μA	Measure 10 times
Combined Standard Uncertainty					40.9 μA		
Expanded Uncertainty (Level of Confidence of approx. 95 %)					82 μA		Calculated with k=2

± 1.5 °C as its limit, which is 0.866 °C ($= 1.5 / \sqrt{3}$ °C), and using the thermoelectromotive force coefficient to convert this value into electromotive force, we obtain 1.13 μ V (0.866 °C \times 1.3 μ V/°C). That is, when measured while differences in terminal voltages are within ± 1.5 °C, standard uncertainty caused by electromotive force is 1.13 μ V.

One can consider the same way if a device under test is connected to the DMM. But one must investigate the metals of the terminals of the device under test, and the thermoelectromotive force coefficients of those metals.

5.2.4 Effects of burden voltage (Only when measuring current)

When measuring current, the DMM's input impedance is ideally 0 Ω , but there is actually a slight input impedance, and a voltage drop occurs between the + terminal and – terminal of the DMM. This voltage drop causes an effect called burden voltage on the standard device and device under test, which is a source of uncertainty. Burden voltage occurs depending on the performance (input impedance) of the DMM used, but the effect created by burden voltage depends on the performance of the standard voltage and current generator. That is, even if a large burden voltage occurred, the effect on calibration results could be large or small. Its degree is written in the instruction manual, and by using those numbers to obtain the value as an upper limit, and a uniform distribution as the probability distribution, the standard uncertainty is estimated. In the combination of the standard device and DMM currently used, we found that the effects of burden voltage can be ignored.

5.3 $u(V_{DUT})$: Uncertainty of measurement results of device under test

When the device under test is connected to DMM and measurements are taken, the V_{DUT} values obtained could have uncertainty due to the following sources, similar to when the standard device is connected and measurements are taken.

5.3.1 Performance of DMM

Same as 5.2.1. The budget table has items written that are aligned with 5.2.1.

5.3.2 Resolution of digital indication of DMM

Same as 5.2.2.

5.3.3 Effects of thermoelectromotive force (Only when measuring DC voltage)

Same as 5.2.3, but there are various types of device under test, so the thermoelectromotive force coefficients of the metal materials of the terminals must be investigated.

5.3.4 Effects of burden voltage (Only when measuring direct current)

Same as 5.2.4, but one must investigate capabilities when affected by the burden voltage of the device under test.

5.4 Variability of calibration results

In a calibration, 1 set is the average value of measurements 100 times; 5 sets are measured, to have effects due to variability sufficiently small compared to other uncertainty sources, and to have sufficiently large effective degrees of freedom.

5.5 Calibration and measurement capability

Tables 3 and 4 shows a sample summary of the results described above. Table 3 has numbers for DC 1 V. Table 4 is for DC current 1 A.

Looking at these tables, a source of large uncertainty is performance of the standard device as described in 5.1.2. To reduce this uncertainty source, one could shorten the time between calibrations at the superior calibration organization, and prepare multiple standard voltage and current generators and ensure there is little change over time.

Table 5 shows a list of calibration and measurement capabilities currently registered by NICT as a JCSS accredited laboratory [7]. As seen in 5.3, values of uncertainty reflect the performance of the device under test, while the calibration and measurement capabilities express the minimum uncertainties obtained when calibrated by the JCSS registered procedures. To obtain the calibration

Table 5 Calibration and measurement capability

		Calibration item		CMC
DC voltage	1 V	—		6.9 μ V
	10 V	—		46 μ V
	100 V	—		590 μ V
DC current	10 mA	—		0.36 μ A
	100 mA	—		4.6 μ A
	1 A	—		82 μ A
	10 A	—		3,200 μ A
AC voltage	10 V	50 Hz, 60 Hz		0.62 mV
		400 Hz		0.58 mV
	100 V	50 Hz, 60 Hz		7.2 mV
		400 Hz		7.0 mV
AC current	100 mA	50 Hz, 60 Hz		16 μ A
	1 A	50 Hz, 60 Hz		300 μ A
	10 A	50 Hz, 60 Hz		4.3 mA

and measurement capabilities, 10 sets of measurements were taken.

6 Conclusion

We explained a method to calibrate a standard voltage and current generator that can generate reference voltage and current for calibrating testers and multi-meters. From calibration principles, we explained the actual calibration procedures, and sources of uncertainty associated with calibration results, and showed calibration and measurement capabilities for calibration items.

Devices for measuring DC voltage and current require handling that differs from that of measurement devices for other radio frequency bands, because they use the lead, instead of the coaxial cable. The required level of measurement precision also differs, several percent for the measurement of radio frequency bands, as opposed to several ppm for the measurement of DC voltage and current, which is two or three decimal places higher in precision level, so one must calibrate with appropriate procedures.

Appendix. Derivation of Equation (1)

The calibration of a standard voltage and current generator is performed by reading the values displayed on the DMM connected to the standard voltage and current generator, when voltage or current is output. Measuring output voltage and current generated from the standard voltage and current generator by a DMM is equivalent to calibrating the DMM by connecting two standard voltage and current generators, and comparing those results.

First, connect the device under test to the DMM, set the indicated value of the device under test to the nominal value V_{NOMINAL} , and read the V_{DUT} value displayed on the DMM when the output is aligned. At that time, the device under test of the calibration value C_{DUT} was used to calibrate the DMM, so the calibration value $C_{\text{DMM}}^{(1)}$ of the DMM can be obtained by the following equation.

$$C_{\text{DMM}}^{(1)} = V_{\text{NOMINAL}} + V_{\text{DUT}} - C_{\text{DUT}} \quad (\text{A.1})$$

Next, connect the standard device to the DMM, and when the indicated value of the standard device is aligned with the nominal value V_{NOMINAL} , read the V_{STD} value displayed on the DMM. Then, the device under test of the calibration value C_{STD} was used to calibrate the DMM, so the calibration value $C_{\text{DMM}}^{(2)}$ of the DMM can be obtained by the following equation.

$$C_{\text{DMM}}^{(2)} = V_{\text{NOMINAL}} + V_{\text{STD}} - C_{\text{STD}} \quad (\text{A.2})$$

Then, when the calibration values $C_{\text{DMM}}^{(1)}$ and $C_{\text{DMM}}^{(2)}$ of the DMM become the same, the standard voltage and current generator of the device under test is calibrated, so in Equations (A.1) and (A.2), $C_{\text{DMM}}^{(1)} = C_{\text{DMM}}^{(2)}$ must be true. Then, V_{NOMINAL} is also deleted from both equations, and Equation (1) in the main text is obtained as follows.

$$C_{\text{DUT}} = +C_{\text{STD}} - V_{\text{STD}} + V_{\text{DUT}} \quad (\text{A.3})$$

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