Fully-Automatic DMM Calibration System

White Paper

Abstract

This paper describes a fully-automatic calibration system for digital multimeters (DMMs), and uncertainty estimation of the DCV measurements of the system. A connection mechanism whose rating is more than 1000 V/1 A/1 MHz was developed for the system. By using compressed air to drive the mechanism, we were able to eliminate operator bias, as well as improve the thermal electromotive force and measurement repeatability of the system. For the standard in the system, an 8 ½ digital multimeter was used, which was calibrated by the standards laboratory of Agilent Technologies Japan Ltd. The measurement uncertainty was estimated by referring to the ISO Guide to the Expression of Uncertainty in Measurement[1] (GUM).

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Issue for Designing Fully-Automatic DMM Calibration System

There are some points to be considered in order to design a digital multimeter (DMM) calibration system, such as traceability to an upper level standards laboratory, selection of a stable standard, and evaluation of the measurement repeatability. Furthermore, for a fully -automatic DMM calibration system, it is necessary to consider signal switching mechanisms, system noise, and countermeasures for abnormal conditions.

Generally, a relay switch is used to route test signals between the unit under test (UUT) and signal sources. However, a relay switch isn't suitable for precision measurement of low voltage because thermal electromotive force (thermal-emf) is caused by self-heating due to the driving current of the relay. Therefore, a commercially available low thermal-emf scanner is widely used for a precision measurement system for a standard cell or a Zener voltage standard. On the other hand, as maximum DC voltage and DC current of the DMM calibration are 1000 V and 1 A, the scanner whose maximum rate is 24 V 0.5 A is unlikely to be used in the fully-automatic DMM calibration system.

Besides, a fully-automatic calibration system is physically larger than a manual calibration system. Because the cables between the equipment become long and are easily affected by environment noise, the problem of measurement repeatability can occur.

Furthermore, as the fully-automatic calibration system can perform calibration without operators, it is important to take countermeasures for unexpected damage to the equipment or the software into consideration.

Design for Fully-Automatic DMM Calibration System

We developed the fully-automatic system in order to improve upon operation quality and throughput of 8½-digit DMM calibration, considering the above-mentioned problems. The calibration parameters are DCV, DCI, DCR, ACV, ACI and frequency at 1 MHz. For example, calibration ranges are from 100 mV to 1 kV for DCV and from 100 µA to 1 A for DCI.

The picture of this system is shown in Figure 1. This system consists of rack A which mounts a standard (STD) unit, maximum six units under test (UUTs) and a sequencer, rack B with voltage/current /resistor signal sources, and a workstation to control the system.

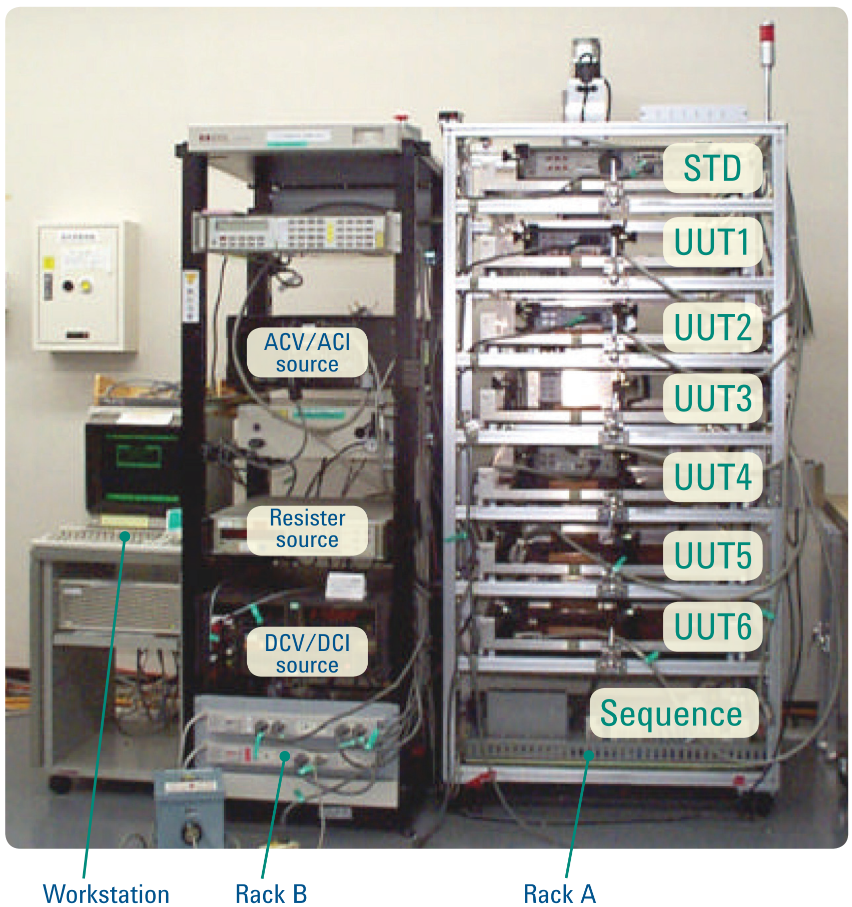

Figure 1.

An 8½-digit DMM which has excellent stability of long term and temperature is used as a STD, and is calibrated by the standards laboratory of Agilent Technologies Japan, Ltd. every three months. And the standards lab is traceable to Electrotechnical Laboratory (ETL), that is, Japanese national standards lab. For routing test signals between UUT and signal sources, a special and low thermal-emf connection mechanism was developed.

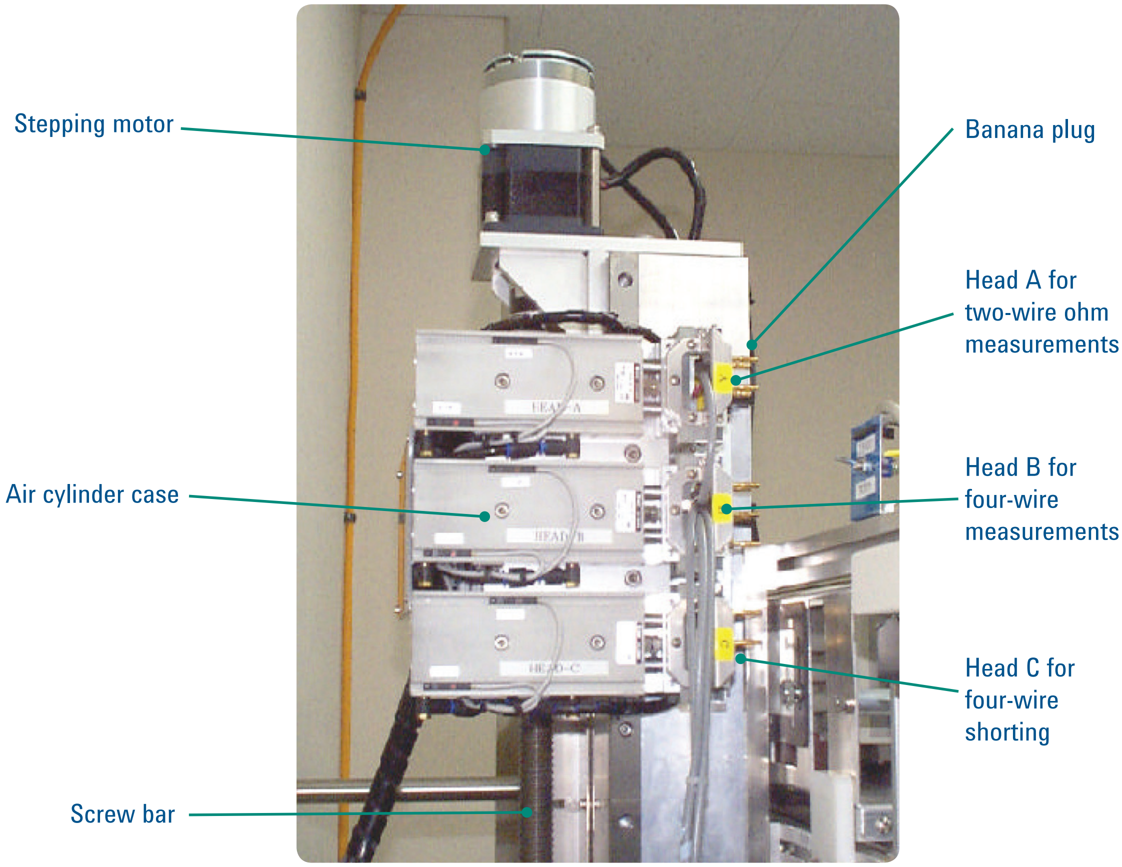

Figure 2.

The picture of the connection mechanism is shown in Figure 2. This connection mechanism consists of a set of three heads for inserting banana plugs into a STD or UUT input terminals, and the driving mechanism for moving the set of heads.

There are three types of heads in the set, one is for two-wire ohm measurements, one is for four-wire measurements, and one is for four-wire shorting. There are six banana plugs in each head, which are put into six input terminals (Input High/Low, Sense High/Low, Current, and Guard terminals) of the STD or UUT. Air cylinders are used which are driven by compressed air to insert these banana plugs into the input terminals. By using compressed air, thermal-emf and influence of the electromagnetic interference is reduced. A stepping motor on the top of rack A rotates screw bar, which moves a set of heads.

The sequencer, which controls air cylinders and the stepping motor of switching mechanism, has the capability to avoid the effect of backlash from the screw bar.

Repeatability caused by environmental noise is improved by triaxial cables.
As the fully-automatic DMM calibration system can perform calibration without operators, it may happen that unexpected single noise affects observed data. To avoid that kind of influence, we have a special algorithm in our software.

Evaluation of Fully-Automatic DMM Calibration System

We measured 900 times to estimate reliability of the system against unexpected noise and didn't identify any malfunction.

Up to six UUTs can be vertically installed and calibrated in rack A of this system. Generally, as a DMM is influenced by environmental temperature, it is important to investigate the temperature distribution of each slot in rack A. The standard deviation of the temperature distribution is ±0.2°, which is less than the control limits of temperature in our standard room of ±1°, therefore it is assumed to not affect measurement.

Observations of a DMM may change with time constant even if a constant voltage is applied to the input of the DMM. We observed the voltage of a DMM varied by 10 ppm over 4 minutes when the DMM was applied at 1000 V. Such time constant can be avoided by setting a waiting time after applying the voltage to UUT input.

In the fully-automatic calibration system, measurement results with excellent repeatability can be obtained because software controls the measurement procedure, such as measurement sequence, waiting time.

Uncertainty Estimation

The uncertainty of DCV calibration for Agilent 3458A, which is estimated by referring to the ISO GUM, is shown in the following sections.

Mathematical Model

The flow diagram of DCV calibration is shown in Figure 3. Numeric data is for calibration of 1 V DC. The calibrated value of the STD described in the standards lab report is the displayed value on the STD V_{MDCC} when nominal voltage (+ 1.0 V) is applied to the STD. When output voltage of the DC voltage source V_{SDC1} is observed by the STD, the difference in voltage between observed voltage of the STD V_{MDCS} and V_{MDCC} is given by,

$$V_{MDCS} - V_{MDCC} = V_{SDC1} - 1\text{V} + \delta_{DCVS} \qquad (1)$$

where δ_{DCVS} is the non-linearity of the STD. The UUT displays the voltage of V_{CDCU} that is defined

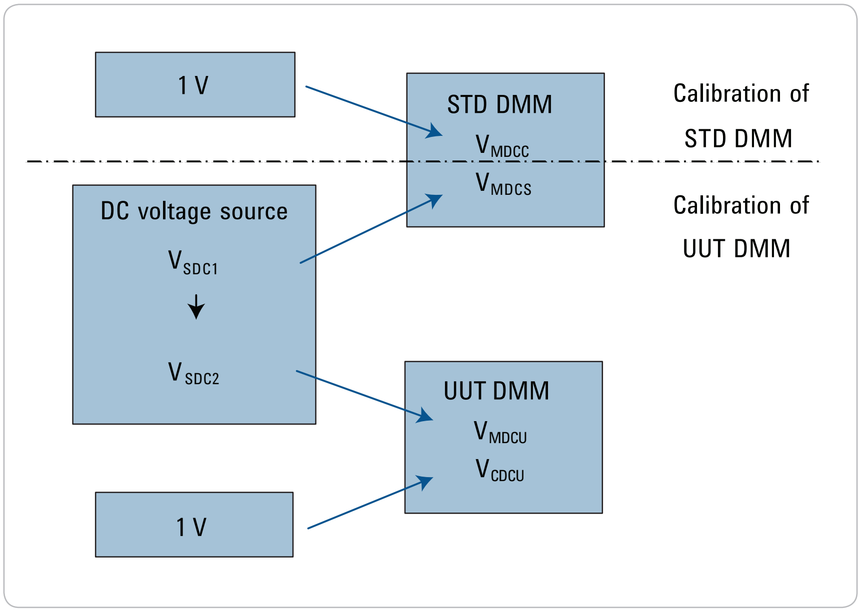

Figure 3.

as the measurand when nominal voltage (+1.0 V) is applied to the UUT. When the output voltage of the DC voltage source V_{SDC2} is observed by a UUT, the difference between observed voltage of the UUT V_{MDCU} and V_{CDCU} is given by,

$$V_{MDCU} - V_{CDCU} = V_{SDC2} - 1\text{V} + \delta_{DCVU} \qquad (2)$$

where δ_{DCVU} is the non-linearity of the UUT. The difference k_{DCV} between the output voltage of DC voltage source V_{SDC1} and V_{SDC2} is given by,

$$V_{SDC2} - V_{SDC1} = k_{DCV} \qquad (3)$$

Thus from equations (1), (2), and (3),

$$V_{CDCU} = V_{MDCC} - V_{MDCS} + \delta_{DCVS} + V_{MDCU} - \delta_{DCVU} - \mathrm{k}_{DCV} \qquad (4)$$

Contributory Variances

The variance of measurand $u_C^2\left(V_{CDCU}\right)$ is,

$$u_C^2\left(V_{CDCU}\right) = c_{VMDCC}^2 u^2\left(V_{MDCC}\right) + c_{VMDCS}^2 u^2\left(V_{MDCS}\right) + c_{\delta DCVS}^2 u^2\left(\delta_{DCVS}\right) + c_{VMDCU}^2 u^2\left(V_{MDCU}\right) + c_{\delta DCVU}^2 u^2\left(\delta_{DCVU}\right) + c_{kDCV}^2 u^2\left(k_{DCV}\right) \quad (5)$$

where each sensitivity coefficient is given by

$$c_{VMDCC} = \frac{\partial V_{CDCU}}{\partial V_{MDCC}} = 1 \qquad c_{VMDCS} = \frac{\partial V_{CDCU}}{\partial V_{MDCS}} = -1 \qquad c_{dDCVS} = \frac{\partial V_{CDCU}}{\partial d_{DCVS}} = 1$$

$$c_{VMDCU} = \frac{\partial V_{CDCU}}{\partial V_{MDCU}} = 1 \qquad c_{\delta DCVU} = \frac{\partial V_{CDCU}}{\partial \delta_{DCVU}} = -1 \qquad c_{kDCV} = \frac{\partial V_{CDCU}}{\partial k_{DCV}} = -1$$

Uncertainty of Calibration of Standard, u(VMDCC)

The uncertainty $u(V_{MDCC})$ of calibration of the STD V_{MDCC} consists of uncertainty $u(V_{MDCC1})$ stated in the calibration report, uncertainty $u(V_{MDCC2})$ caused by drift of the STD, and uncertainty $u(V_{MDCC3})$ caused by the difference in internal temperatures of the STD.

$u(V_{MDCC1})$: Expanded standard uncertainty stated in the calibration report is shown in Table 1. Coverage factor k = 2.

$u(V_{MDCC2})$: The drift of the calibrated value of the STD is estimated from previous calibration to be zero within the bounds. The bounds are shown in Table 2, with an equal probability.

$u(V_{MDCC3})$: The internal temperature of the STD when performing UUT calibration may not be the same as that stated in the calibration report. The difference in internal temperatures causes uncertainty. The internal temperature of the STD stated in the calibration report is 35.0 °C. On the other hand, from our experiment, the internal temperature of the STD when performing UUT calibration observed was from 37.5 °C to 39.0 °C. According to the result, the mid-point of the internal temperature is (37.5 °C +39.0 °C)/2 = 38.3 °C. Therefore the difference in internal temperatures of the STD is (38.3 °C – 35.0 °C) = 3.3 K. Temperature coefficient in DCV measurement is given by the manufacturer's specification[2] with equal probability and is shown in table 3, consequently $u(\delta_{CDCV3})$ is given by the uncertainty of temperature coefficient and the difference in internal temperatures.

Table 1.

	Relative uncertainty $k = 2$	Standard uncertainty $u(V_{MDCC1})$
0.1 V	4.8 ppm	0.24 μV
1.0 V	4.1 ppm	2.05 μV
10 V	0.80 ppm	4.0 μV
100 V	3.4 ppm	0.17 mV
1000 V	3.5 ppm	1.75 mV

Table 2.

	Bound of drift	Standard uncertainty $u(V_{MDCC2})$
0.1 V	0.37 μV	0.21 μV
1.0 V	3.2 μV	1.8 μV
10 V	14 μV	8.1 μV
100 V	0.24 mV	0.14 mV
1000 V	9.4 mV	5.4 mV

Table 3.

	Manufacturer's specification	Uncertainty of temperature coefficient	Difference in internal temperature	Uncertainty $u(V_{MDCC3})$
0.1 V	1.15 ppm/K	0.66 ppm/K	3.3 K	0.22 μV
1.0 V	0.25 ppm/K	0.14 ppm/K	3.3 K	0.46 μV
10 V	0.16 ppm/K	0.092 ppm/K	3.3 K	3.0 μV
100 V	0.25 ppm/K	0.14 ppm/K	3.3 K	46 μV
1000 V	0.16 ppm/K	0.092 ppm/K	3.3 K	0.30 mV

Uncertainty of Repeated Observations of STD and UUT, $s(V_{MDCS})$, $s(V_{MDCU})$

Scatter in observation of the STD and the UUT would be caused by irregular changes of output voltage of DCV source, by thermal noise and by irregular changes of input bias current of the STD and the UUT. The experimental standard deviations of V_{MDCS} and V_{MDCU} can be observed by displayed value on the STD and the UUT, as shown in Table 4. The standard uncertainties $u(VMDCS)$ of $VMDCS$ and $u(V_{MDCU})$ of V_{MDCU} are $u(V_{MDCS}) = s(V_{MDCS})$ and $u(V_{MDCU}) = s(V_{MDCU})$, respectively.

Uncertainty of Non-linearity of STD and UUT, $u(\delta_{DCVS})$, $u(\delta_{DCVU})$

Non-linearity of the STD and the UUT are assumed to be 0.1 ppm[3] with equal probability. Therefore the standard uncertainty is then 0.1 ppm/$\sqrt{3}$= 0.058 ppm, as shown in Table 5.

Table 4.

	Uncertainty $s(V_{MDCS})$
0.1 V	66 nV
1.0 V	0.26 μV
10 V	0.60 μV
100 V	12 μV
1000 V	0.15 mV

Table 5.

	Relative uncertainty	Uncertainty $u(\delta_{DCVS})$
0.1 V	0.058 ppm	5.8 nV
1.0 V	0.058 ppm	58 nV
10 V	0.058 ppm	0.58 μV
100 V	0.058 ppm	5.8 μV
1000 V	0.058 ppm	58 μV

Uncertainty of k_{DCV}, $u(k_{DCV})$

Uncertainty $u(k_{DCV})$ is the short-term drift of the DC voltage source. The drift k_{DCV} is expected to be zero. The estimated bounds on the variability of k_{DCV} were determined from observations of the DC voltage source with the STD for 12 hours and found to be the values in Table 6.

Table 6.

	Uncertainty $u(k_{DCV})$
0.1 V	0.18 µV
1.0 V	0.44 µV
10 V	1.7 µV
100 V	68 µV
1000 V	0.56 mV

Combined Standard Uncertainty

The combined standard uncertainties of measurand in each range are estimated from the above-mentioned uncertainty of each input quantity and each sensitivity coefficient, and are shown in Table 7.

Table 7.

	$\lvert c_{VMDCC} \times u(V_{MDCC}) \rvert$	$\lvert cV_{MDCS} \times u(V_{MDCS}) \rvert$	$\lvert c\delta_{DCVS} \times u(\delta_{DCVS}) \rvert$	$\lvert cV_{MDCU} \times u(V_{MDCU}) \rvert$	$\lvert c\delta_{DCVU} \times u(\delta_{DCVU}) \rvert$	$\lvert c_{kDCV} \times u(k_{DCV}) \rvert$	$\frac{u_c(V_{CDCU})}{V_{CDCU}}$
0.1 V	0.387 µV	0.066 µV	0.0058 µV	0.066 µV	0.0058 µV	0.18 µV	4.4 ppm
1.0 V	2.77 µV	0.26 µV	58 nV	0.26 µV	58 nV	0.44 µV	2.9 ppm
10 V	9.52 µV	0.60 µV	0.58 µV	0.60 µV	0.58 µV	1.7 µV	0.98 ppm
100 V	225 µV	12 µV	5.8 µV	12 µV	5.8 µV	68 µV	2.4 ppm
1000 V	5.68 mV	0.15 mV	0.058 mV	0.15 mV	0.058 mV	0.56 mV	5.8 ppm

Conclusion

We developed a fully-automatic DMM calibration system which has a special switching mechanism driven by compressed air to reduce thermal emf effect. The STD of this system is traceable to ETL via standards lab of Agilent Technologies Japan, Ltd. We estimated uncertainty in the system by referring to the ISO GUM. Dominant factors of uncertainty are caused by the STD and the short-term drift of the DC voltage source. Uncertainty caused by repeatability in measurement is not a dominant factor. The software has several special routines to avoid abnormal conditions or unexpected signal noise in order to perform calibration without operators, therefore, operation quality and throughput of calibration is improved. The fully-automatic DMM calibration system we developed has such excellent measurement repeatability that it is suitable for accurate and reliable measurements.

References

[1] *ISO Guide to the Expression of Uncertainty in Measurement,* 1993 (E)

[2] *Operation Manual of HP 3458A Multimeter,* Hewlett Packard Company

[3] Wayne Goeke, HP "*Technical Requirements of Self/Auto Calibration Techniques*"

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