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Measurement uncertainty improvement on electric current calibration using precision shunts

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Abstract. This paper presents the improvements in measurement uncertainty in calibration of electric current sources obtained by replacing the direct measurement method, using a precision digital multimeter, by an indirect method that uses precision shunts. An analysis of the sources of uncertainty that must be considered in this indirect method is also carried out. Finally, two examples of indirect calibration of a precision current source using shunts as a standard are shown.

1. Introduction

Precision digital multimeters (DMMs), such as 8 ½ digit ones (Fluke 8588A, Keysight 3458A, etc.) are common instruments in electrical calibration laboratories, and they are often used as reference standards in voltage, current and resistance measurements due to their key characteristics and ultimate performance. Despite its excellent performance, in certain electrical calibration laboratories, often a precision digital multimeter fails to provide adequate test uncertainty ratio (TUR) or test acceptance ratio (TAR) for the calibration of some instruments, such as their own working standards – for example, multifunction calibrators. This is the case of calibration of electric current measuring instruments, where TAR is close to 1. In this situation, to obtain a more adequate TUR or TAR, greater than or equal to 3, the precision multimeter must be replaced by another standard that provides better measurement uncertainty. One option to replace the precision multimeter is precision shunts, which should be used together with a precision voltage measuring instrument.

This paper presents measurement uncertainty analysis and estimation of current source calibration using precision shunts and precision voltmeter. The measurement uncertainty obtained is also compared with the measurement uncertainty obtained by the traditional precision digital multimeter method. Section 2 presents the main characteristics of shunts. Section 3 details both measurement methods. Section 4 presents and discusses the uncertainty sources that should be considered in the indirect method. Section 5 shows two current source calibration examples using precision shunts, one DC current and one AC current. Finally, Section 6 presents some conclusions.

2. Precision shunts

Shunts are very precise resistors inserted into a circuit to measure the current flowing through that circuit. The principle of operation of the current shunt is very simple: it converts a current flowing through it into a proportional voltage drop, which can be measured with voltmeter or a thermal voltage converter (TVC). This can be clarified using Ohm’s Law, which states that the voltage will be equal to the current multiplied by the resistance. The resistance of the shunt should be small to reduce power dissipation but sufficiently high to measure the voltage drop with required accuracy, e.g., equal to approximately 1 V. Figure 1 shows a basic electrical circuit with a shunt.

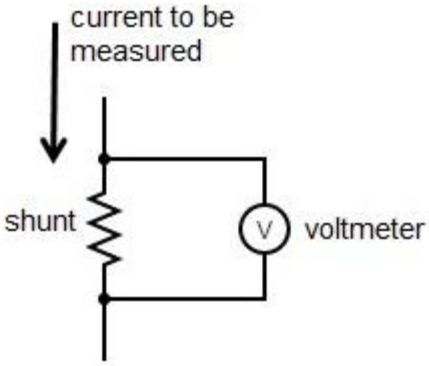

Figure 1. Basic electrical circuit with a shunt.

For precision shunts, it is desirable to exhibit good self-heating power coefficient, low temperature coefficient, both phase shift and AC-DC transfer difference close to zero and a flat frequency response. These characteristics will be used as sources of uncertainty and need to be estimated. [1]-[3].

3. Calibration methods

The traditional electric current source calibration method employs a precision DMM, that directly measures the generated current. The mathematical model of this measurement is given by (1), where I_X is the current from the source, I_S is the current measured by the DMM and δI_S is the correction due to systematic effects of the DMM, such as resolution, drift from last calibration and temperature. I_S is estimated on a set of at least three measurements and on the DMM's last calibration report. δI_S can be obtained on the technical documentation provided by the DMM's manufacturer. Considering the calibration of a 10 A DC current sourced by a Fluke 5720A multifunction calibrator, measured by a Fluke 8588A DMM, standard measurement uncertainty estimated for a 1-year calibration interval cycle is about 0.021% and TAR is about 1.9. As the TAR value is less than 4 (or even 3), the measurement is considered inappropriate [4].

$$I_X = I_S + \delta I_S \tag{1}$$

In the new calibration method, the direct measurement of the electrical current by the precision multimeter is replaced by an indirect measurement, which uses a shunt in series with the current source, and a voltmeter, which measures the voltage drop in the shunt (see Figure 1). The voltmeter can even be the same precision DMM used in direct measurement. The mathematical model of this measurement can be seen in (2), where V_S is the voltage drop measured by the precision DMM, δV_S is the correction due to systematic effects of the DMM, R_S is the shunt's resistance and δR_S is the correction due to systematic effects of the shunt. Section 4 will discuss measurement uncertainty obtained with the use of precision shunts.

$$I_X = \frac{V_S + \delta V_S}{R_S + \delta R_S} \tag{2}$$

4. Uncertainty sources

In the new calibration method, the direct measurement of the electrical current by the precision multimeter is replaced by an indirect measurement, which uses a shunt in series with the current source, and a voltmeter, which measures the voltage drop in the shunt (see Figure 1). The voltmeter can even be the same precision DMM used in direct measurement. In this method, uncertainty sources come from the DMM voltage measurement and from the shunt's resistance.

The corrections and their uncertainties from the shunt's resistance are due to: (a) last calibration report; (b) drift since last calibration; (c) temperature variations; (d) self-heating due to application of the current to be measured (power coefficient); (e) humidity influence; (f) AC-DC difference or frequency influence; and (g) loading influence. Some of these uncertainty sources are discussed below.

Uncertainty due to drift of shunt's resistance can be obtained from historical data, if available, otherwise it can be estimated from technical documentation, such as manuals, datasheets, and others. It is frequent practice for current shunts to be calibrated at a single current level and then used over a wide range of currents. The power coefficient of the shunt can contribute significantly to the measurement quality. Uncertainty due to power coefficients can be estimated in different ways: experimentally, calibrating the shunt at several currents, using a modified current-bridge method, or characterizing the power coefficient with a shunt of known power coefficient, or through technical documentation of the shunt. Power coefficient can be different for AC and DC currents, for precise measurements [2],[5].

If the shunt is calibrated only at DC current, and it needs do be used with AC current, then an estimation of the AC-DC difference should be performed. In the uncertainty budget, dependence of the AC–DC difference of the shunts is very often the dominant part, particularly at high frequencies. This estimation should be part of the calibration report of the shunt, and its stability can be obtained from the technical documentation. This difference also can be estimated by calibrating the shunt at several frequencies [6],[7].

The specifications from technical documentation for a shunt represent its performance under ideal conditions. In practical use, placing the input of the voltage measurement device in parallel with the shunt introduces an additional impedance (loading effect) which will result in a measurement error. For the non-active current shunts, the loading effect becomes more significant as the resistance value of shunt increases, that is, as the nominal current value decreases. For the most accurate measurements, the error due to this loading effect must be calculated and used as a measurement correction [8].

5. Current source calibration

After identifying and estimating uncertainty sources, they should be combined to estimate the standard uncertainty of the current source calibration, using the methodology defined by [9]. Two examples will be discussed below. In both, a Fluke 5720A multifunction calibrator is calibrated using a Fluke A40B-10A precision shunt and a 8588A DMM for voltage drop measurements. The 5720A multifunction calibrator and the A40B-10A are shown in Figure 2.

Figure 2. Fluke 5720A multifunction calibrator and Fluke A40B-10A.

Table 1 shows an example of an uncertainty budget of a 5720A multifunction calibrator at 10 A DC, using a Fluke A40B-10A-80mΩ shunt and a Fluke 8588A DMM for voltage drop measurement, where R_S is the shunt's resistance according to its last calibration report, $\delta R_{S.S}$ is the correction of the shunt's resistance due to stability since last calibration, $\delta R_{S.PC}$ is the correction due to shunt's power coefficient, $\delta R_{S.T}$ is the correction due to temperature variation influence on the shunt, δL is the correction due to the loading effects, V_S is the voltage drop measured by the DMM and $\delta V_{S.S}$ is the stability of the DMM since its last calibration. The shunt is calibrated at 10 A and variations in DMM readings are of little significance. The measurement uncertainty is about 8.8 times lower than traditional method measurement uncertainty.

Table 1: Uncertainty budget for 5720A calibration with 8588A DMM and A40B-10A shunt at 10 A DC.

Quantity X_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
R_S	0.44 µΩ	Normal	-125 A/Ω	0.10 mA
$\delta R_{S.S}$	0.83 µΩ	Rectangular	-125 A/Ω	55 µA
$\delta R_{S.PC}$	0 Ω	Rectangular	-125 A/Ω	0 µA
$\delta R_{S.T}$	0 Ω	Rectangular	-125 A/Ω	0 µA
δL	3.7 nV	Rectangular	12.5 Ω^{-1}	46 nA
V_S	0.34 µV	Normal	12.5 Ω^{-1}	4.3 µA
$\delta V_{S.S}$	1.2 µV	Normal	12.5 Ω^{-1}	15 µA
$\delta V_{S.R}$	2.9 nV	Rectangular	12.5 Ω^{-1}	36 nA
Combined standard uncertainty $u_c(y)$ =	0.12 mA or 12 µA/A			

Table 2 shows the uncertainty budget of the same 5720A multifunction calibrator at 10 A AC (60 Hz), using the same Fluke A40B-10A-80mΩ shunt and Fluke 8588A DMM for voltage drop measurement. $\delta R_{S.ACDC}$ is the correction due to the AC-DC difference of the shunt. Its uncertainty is the combination of the uncertainty from the calibration report and the uncertainty due to stability. This measurement uncertainty is about 9.6 times lower than traditional method measurement uncertainty. Figure 3 shows the measurement uncertainty improvements for both DC and AC currents.

Table 2: Uncertainty budget for 5720A calibration with 8588A DMM and A40B-10A shunt at 10 A AC (60 Hz).

Quantity X_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
R_S	0.44 µΩ	Normal	-125 A/Ω	55 µA
$\delta R_{S.S}$	0.83 µΩ	Rectangular	-125 A/Ω	0.10 mA
$\delta R_{S.PC}$	0 Ω	Rectangular	-125 A/Ω	0 µA
$\delta R_{S.T}$	0 Ω	Rectangular	-125 A/Ω	0 µA
$\delta R_{S.ACDC}$	2.0 µΩ	Normal	-125 A/Ω	0.26 mA
δL	3.7 nV	Rectangular	12.5 Ω^{-1}	46 nA
V_S	7.6 µV	Normal	12.5 Ω^{-1}	95 µA
$\delta V_{S.S}$	26 µV	Normal	12.5 Ω^{-1}	0.33 mA
$\delta V_{S.R}$	29 nV	Rectangular	12.5 Ω^{-1}	0.36 µA
Combined standard uncertainty $u_c(y)$ = 0.44 mA or 44 µA/A				

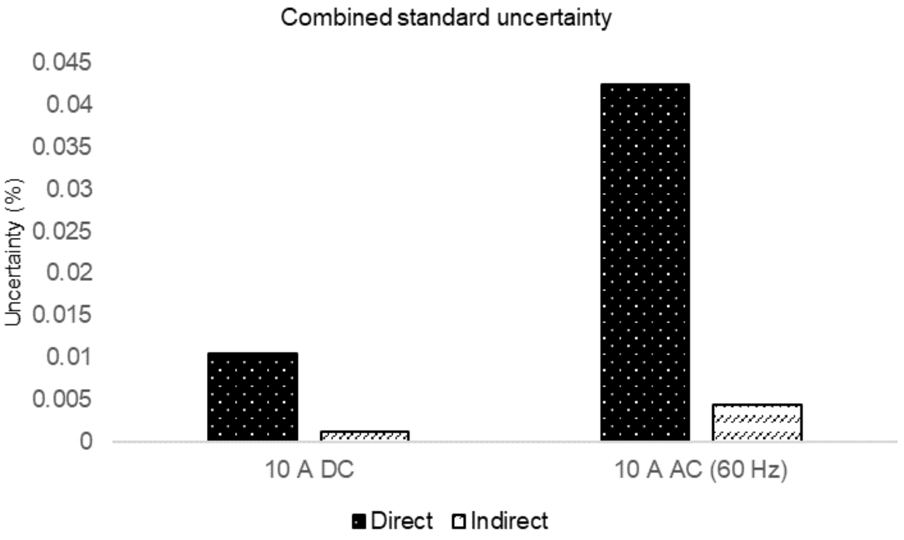

Figure 3. Measurement uncertainty for 10 A DC and 10 A AC (60 Hz) calibration using direct and indirect methods.

6. Conclusion

This paper presented the measurement uncertainty improvements on current sources calibrations, by replacing the direct measurement method by an indirect measurement method using precision shunts. Two calibration examples were discussed, where measurement uncertainty improvements were 8.8 (DC current) and 9.6 (AC current). Uncertainty sources of the indirect measurement method were also presented and detailed.

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