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Measurement uncertainty improvement on electric current sources calibration using precision shunts

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ABSTRACT
This paper presents the improvement in measurement uncertainty in the calibration of electric current sources obtained by replacing the direct measurement method, using a precision digital ammeter, with an indirect method that uses precision shunts and a precision voltmeter. An analysis of the sources of uncertainty that should be considered in this indirect method is also performed. Finally, two examples of indirect calibration of a precision current source using a precision shunt as standard are shown and their results are compared with the results of direct calibrations, highlighting the reduction in measurement uncertainty.

Section: RESEARCH PAPER

Keywords: Electric current calibration; indirect calibration; precision shunts; measurement uncertainty

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1. INTRODUCTION

Electric current sources can be easily calibrated using precision ammeters by the direct measurement method, where these ammeters are mostly provided by precision digital multimeters (DMMs), such as 8 ½ digit ones (Fluke 8588A, Keysight 3458A, etc.), that are common instruments in electrical calibration laboratories, and 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 electric current sources, such as their own working standards (for example, multifunction calibrators), where TAR is the ratio of the maximum permissible error of the instrument under calibration to the maximum error of the standards and TUR is the ratio of the maximum permissible error of the instrument under calibration to the measurement uncertainty of the calibration [1]. In this situation, to obtain a higher TUR or TAR, greater than or equal to 3, the direct method must be replaced by other calibration method that provides better measurement uncertainty. One option to replace the precision ammeter is precision shunts, which must be used in conjunction with a precision voltage measuring instrument, a voltmeter. As in the case of the direct method ammeter, the voltmeter used can be a precision DMM in the voltage function.

When using only the precision ammeter as a standard, the calibration method is direct, as the ammeter will directly indicate the electrical current in the circuit. However, when replacing the precision ammeter with a precision shunt and a voltmeter, the calibration method becomes indirect, as the electric current will be calculated through the resistance value of the shunt and the voltage drop across it, using Ohm's law. In this indirect calibration method, the number of sources of uncertainty is greater, since there is more than one standard involved, and the estimation of measurement uncertainty should be more rigorous, since the aim is to reduce the value of this uncertainty. Some sources of uncertainty should be carefully evaluated.

This paper presents the estimation of measurement uncertainty in the calibration of electric current sources, using precision shunts and a voltmeter as standards. The measurement uncertainty obtained is also compared with the measurement uncertainty obtained by the direct method. Section 2 presents the main characteristics of precision shunts. Section 3 details direct and indirect calibration methods. Section 4 presents and discusses the uncertainty sources that should be considered in the indirect method. Section 5 shows two electric current source calibration examples using precision shunts, one for DC current and the other for AC current. Section 6 discusses the technical and economic issues of replacing the direct method with the indirect method, and finally Section 7 presents some conclusions.

2. PRECISION SHUNTS

Precision 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 a 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 for current measurement with a shunt and a voltmeter.

Among their various characteristics, it is desirable that precision shunts 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. [2]-[4].

Precision shunts have been widely used in applications requiring high stability and low measurement uncertainty, including applications in National Metrology Institutes (NMIs). Nováková et al. [5] developed cage-type shunts that presented an AC-DC difference of 6 μA/A, from 30 mA to 10 A, in the frequency range up to 100 kHz. Ilić et al. [6] developed a method for calibrating AC current sources or meters, in the range of 2 mA to 2 A at a frequency close to the fundamental frequency, with uncertainty in the order of units of μA/A, using precision shunts and an AC quantum voltmeter as standards and a Fluke 5720A multifunction calibrator as current source under calibration. Isaiev et al. [7] developed a method for comparing AC current measurements with equivalent DC current measurements, using thermal converters and shunts. One of the shunts used was a Fluke A40B, with an uncertainty due to the AC-DC difference of 32 μA/A at 20 A and 50 kHz. Lillo et al. [8] developed three precision shunts for 5 A and 10 A and achieved an AC-DC difference of about 25 μA/A at 5 A and 100 kHz for one of them. Voljč et al. [9] developed and evaluated a shunt for nominal current of 100 A and achieved a measurement uncertainty of 75 μA/A from 40 Hz to 30 kHz.

3. CALIBRATION METHODS

The traditional electric current source calibration direct method employs a precision ammeter, that directly measures the generated current. The mathematical model of this measurement is given by equation (1)

$$I_{\mathrm{X}} = I_{\mathrm{S}} + \delta I_{\mathrm{S}}\,, \qquad (1)$$

where I_{X} is the current from the source, I_{S} is the current measured by the ammeter and δI_{S} is the correction due to systematic effects of the ammeter, such as resolution, drift from last calibration and temperature. I_{S} is estimated on a set of at least three measurements and on the ammeter's last calibration report. δI_{S} can be obtained on the technical documentation provided by the ammeter's manufacturer. Considering the calibration of a 10 A DC current sourced by a Fluke 5720A multifunction calibrator, measured by a Fluke 8588A DMM at DC current function, 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 [1]. In the new calibration method, the direct measurement of the electrical current by the precision ammeter 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 mathematical model of this measurement can be seen in (2)

$$I_{\mathrm{X}} = \frac{V_{\mathrm{S}} + \delta V_{\mathrm{S}}}{R_{\mathrm{S}} + \delta R_{\mathrm{S}}}\,, \qquad (2)$$

where V_{S} is the voltage drop measured by the precision voltmeter, δV_{S} is the correction due to systematic effects of the voltmeter, 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.

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 the 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 common 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 characterising 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], [10].

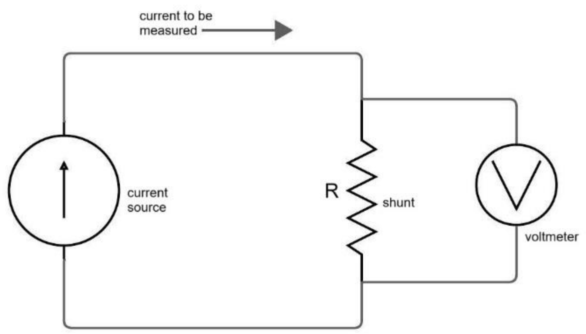

Figure 1. Basic electrical circuit with a shunt.

If the shunt is calibrated only at DC current, and it needs to 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 can also be estimated by calibrating the shunt at several frequencies [11], [12].

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 [13].

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 [14]. Two examples will be discussed below. In both, a Fluke 5720A multifunction calibrator is calibrated using a Fluke A40B-10A precision shunt and an 8588A DMM for voltage drop measurements. The 5720A multifunction calibrator and the A40B-10A are shown in Figure 2.

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 the Fluke 8588A DMM for voltage drop measurement, where R_{S} is the shunt's resistance according to its last calibration report, $\delta R_{\mathrm{S.S}}$ is the correction of the shunt's resistance due to stability since last calibration, $\delta R_{\mathrm{S.PC}}$ is the correction due to shunt's power coefficient, $\delta R_{\mathrm{S.T}}$ 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, $\delta V_{\mathrm{S.S}}$ is the correction due to the stability of the DMM since its last calibration and $\delta V_{\mathrm{S.R}}$ is the

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

correction due to the resolution of the DMM. The shunt is calibrated at 10 A and measurements on the multimeter are performed after the shunt has warmed up, causing variations in DMM readings of little significance. The measurement uncertainty is about 8.8 times lower than traditional method measurement uncertainty.

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. $\delta R_{\mathrm{S.ACDC}}$ 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 the traditional method measurement uncertainty. Figure 3 shows the measurement uncertainty improvements for both DC and AC currents.

6. ANALYSIS OF RESULTS

The calibration results shown in the previous section demonstrated that measurement uncertainty in calibrating DC

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	55 µA
$\delta R_{\mathrm{S.S}}$	0.83 µΩ	Rectangular	-125 A/Ω	0.10 mA
$\delta R_{\mathrm{S.PC}}$	0 Ω	Rectangular	-125 A/Ω	0 µA
$\delta R_{\mathrm{S.T}}$	0 Ω	Rectangular	-125 A/Ω	0 µA
δL	64 fV	Rectangular	12.5 Ω^{-1}	0.8 pA
V_{S}	0.34 µV	Normal	12.5 Ω^{-1}	4.3 µA
$\delta V_{\mathrm{S.S}}$	1.2 µV	Normal	12.5 Ω^{-1}	15 µA
$\delta V_{\mathrm{S.R}}$	2.9 nV	Rectangular	12.5 Ω^{-1}	36 nA
Combined standard uncertainty $u_C(y)$		0.12 mA or rel. 12 µA/A		

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
$\delta R_{\mathrm{S.S}}$	0.83 µΩ	Rectangular	-125 A/Ω	0.10 mA
$\delta R_{\mathrm{S.PC}}$	0 Ω	Rectangular	-125 A/Ω	0 µA
$\delta R_{\mathrm{S.T}}$	0 Ω	Rectangular	-125 A/Ω	0 µA
$\delta R_{\mathrm{S.ACDC}}$	2.0 µΩ	Normal	-125 A/Ω	0.26 mA
δL	1.9 nV	Rectangular	12.5 Ω^{-1}	24 nA
V_{S}	7.6 µV	Normal	12.5 Ω^{-1}	95 µA
$\delta V_{\mathrm{S.S}}$	26 µV	Normal	12.5 Ω^{-1}	0.33 mA
$\delta V_{\mathrm{S.R}}$	29 nV	Rectangular	12.5 Ω^{-1}	0.36 µA
Combined standard uncertainty $u_C(y)$		0.44 mA or rel. 44 µA/A		

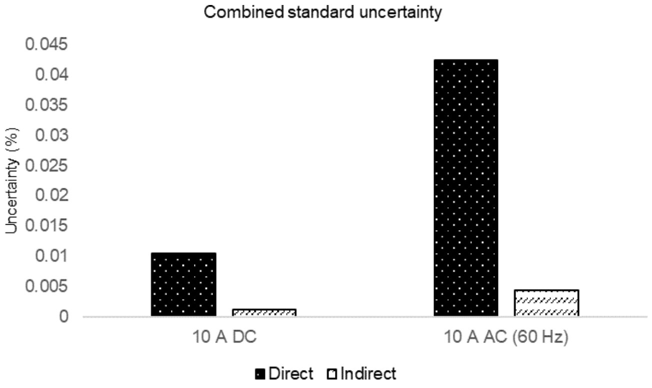

Figure 3. Measurement uncertainty for 10 A DC and 10 A AC (60 Hz) calibration using direct and indirect methods.

and AC electric current sources can be significantly reduced by replacing the direct method that uses a precision ammeter with the indirect method with precision shunts. In this analysis, the focus was only on technical issues and measurement quality.

To more comprehensively evaluate the implementation of the indirect method using precision shunts, the economic aspect must also be considered: new standards (precision shunts) must be acquired, and there will also be the cost of their periodic calibration, which, depending on depending on their characteristics and target uncertainty, they should be carried out at shorter or longer intervals, normally 1 year or 2 years, for example. The cost of periodically calibrating the precision digital multimeter that is used as ammeter in the direct method and as voltmeter in the indirect method will remain, although it may be reduced, as it will no longer be necessary to calibrate it in direct current or alternating current functions, but only in some direct and alternating voltage ranges voltage functions. Therefore, it is quite likely that the final cost of the calibration system will be higher in order to obtain better measurement uncertainty, the benefit of which must be carefully analysed for the laboratory or area where it will be implemented.

7. CONCLUSION

This paper presented the measurement uncertainty improvements on current sources calibrations, by replacing the direct measurement method using an ammeter by an indirect measurement method using precision shunts and digital voltmeter. Two examples of current source calibration using the indirect method, one for DC current and the other for AC current, were presented and their results discussed. When their results were compared with the results of similar calibrations using the direct method, a reduction in measurement uncertainty of 8.8 (DC current) and 9.6 (AC current). The uncertainty spreadsheets of the indirect method were also presented, where it was observed that the largest uncertainty contributions are those due to the long-term stability of the shunt (DC current) and the temporal stability of the voltmeter (AC current). Finally, it was assessed that replacing the direct method with the indirect method must take into account the economic aspect, in addition to technical issues, since the new method, to be implemented, will require investments in the acquisition of precision shunts, as well as expenses with their calibration at regular intervals.

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