Influence of noise in DC current measurements in the range of 0.1 nA - 1 mA

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***Abstract* — This article describes theoretical and experimental studies of the noise influence in direct current measurements by means of measures of voltage and resistance, as well as by serial precision ammeters and DC current calibrators.**

It was shown that the shot noise restrict the measurement accuracy level of dc current in this measurement range.

***Index Terms* — DC current measurement, noise, resistance reference, voltage reference.**

I. Introduction

The upcoming redefinition of the ampere discussed in [1] and the ongoing development of the instruments measuring direct current based on single-electron tunneling [2] in the range up to 1 nA necessitate creating new devices for precision calibration of ammeters and current calibrators, whose operation is based on the use of voltage and resistance references.

It is known that the accuracy in current measurements using this method is limited both by noises, mainly by the thermal and shot noises, and by properties of electronic components and circuits used in precision instruments.

The paper discusses the issue of measurement accuracy limitations due to the noises occurring in dc current measurements in the range from 0.1 nA to 1 mA.

II. Main Limitations

In the measurement of the current I by means of the resistance R and the voltage U, the main limiting factors affecting the accuracy are

- the thermal noise of resistance

$$I_R = (4K_B T R^{-1} \Delta f)^{0.5}, \quad (1)$$

where K_B is the Boltzmann constant, T - temperature of resistor, Δf - bandwidth;

- discrete nature of the measured current, which, in the absence of synchronization of charged particles, is characterized by the shot noise

$$I_q = (2eI\Delta f)^{0.5}, \quad (2)$$

where e is the electron charge.

The noise of the voltage source U_V based on the Josephson effect estimated as being less than 3 nV in the band of 0.01 Hz makes no significant contribution to the combined current noise.

The value of the combined current noise is calculated from the equation

$$dI = (I_R^2 + I_q^2)^{0.5}. \quad (3)$$

Resistance values R are selected depending on the measured dc current in order to achieve high accuracy, considering limitations of voltage and allowable power. The values of relative current noises in the frequency band of 0.01 Hz, calculated for the voltage range of 0.1 V - 10 V and the resistance range of 0.01 - 1000 MΩ are shown in Fig. 1.

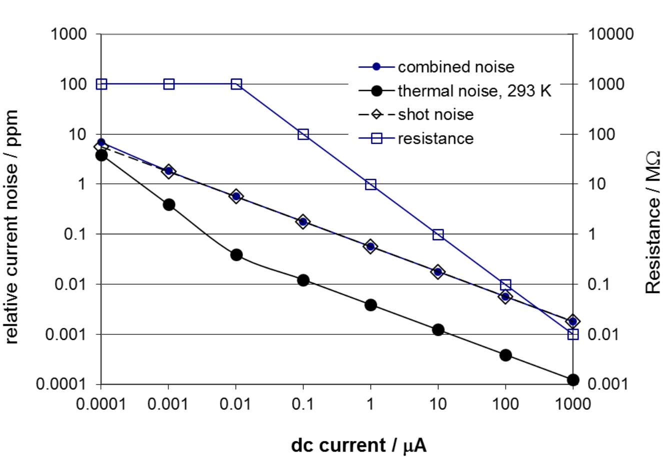

Fig.1 Relationship between relative current noises and dc current, which is formed by resistors and sources of voltage, in the bandwidth of 0.01 Hz

As can be seen from the graph, the main factor limiting the accuracy of current measurement in this range is the shot noise.

When a Zener diode is used as the voltage source it is necessary to take into account both the effect of the voltage noise in the band of 0.01 Hz and the appearing 1/f noise from Zener diodes. The voltage noise U_V for precision voltage reference (without drift) can be determined from the expression [3]:

$$U_V = (0.5k_1^2\Delta f + 2\ln 2 k_2^2)^{0.5}, \quad (4)$$

where k_1 – coefficient of white noise, k_2 – coefficient of $1/f$ noise. In this case, the value of the combined current noise can be presented as

$$dI/I = ((I_R/I)^2 + (I_q/I)^2 + (U_V/U)^2)^{0.5}. \quad (5)$$

Usual values for precision Zeners (k_1 = 0,14 µV/Hz$^{-1/2}$, k_2 = 0,06 µV, U = 10 V) give the voltage noise that produce a current noise comparable with the shot noise, and this current does not allow reducing measurement uncertainty for the currents measured at levels above 1 mA.

II. Measuring Current Noise of Precision Devices

The following serial precision instruments were used for the investigation:

ammeters Keithley 6430, Agilent 3458A, Fluke 8508A, ammeters based on resistances and voltmeters Keithley 6430, Agilent 3458A, Fluke 8508A, Agilent 34420A;

dc current calibrators Keithley 6430, Belwar HK4-1 Belarus, RITM H-12 Russia.

The ammeters were investigated by supplying current to an ammeter input from voltage source through resistance (Fig. 2). The current calibrators were investigated using the scheme (Fig. 3), in which currents difference was measured by means of a null detector.

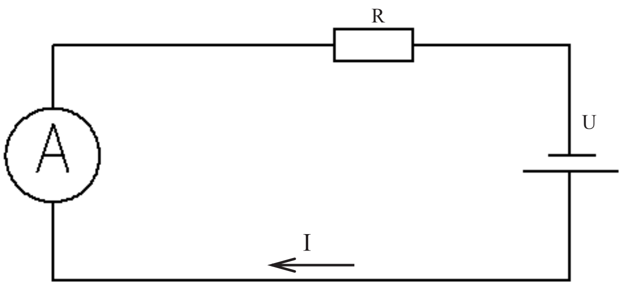

Fig.2 Scheme used to investigate the ammeters

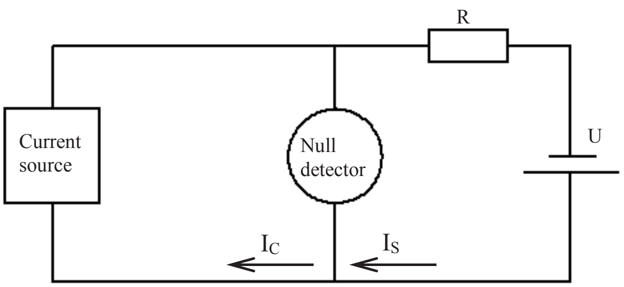

Fig.3 Scheme used to investigate the current calibrators.

The results obtained for the relative current noise from investigated devices with respect to the measured current are shown on Figure 4. The same Fig. shows the curve of the combined noise calculated by equation 5 and also the curve featuring a best accuracy of these instruments taking from their specifications.

The curve for the combined noise displays a lower limit of the relative current noise near 0.01 ppm with respect to the voltage noise from Zener.

Measurement points of ammeters and calibrators are located above those of the combined noise, some of them being close to the limit, the others differing by two orders of magnitude.

All points are located below the best values given in the specifications of the investigated instruments (Fig.4).

The result of 1 mA measurement obtained with 10 V Zener and 10 kΩ resistance is shown in Fig.5.

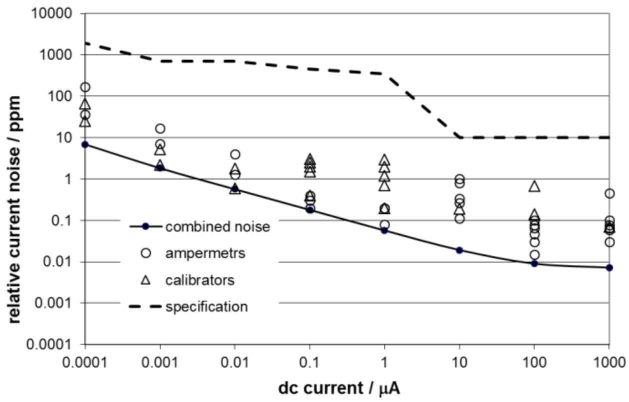

Fig.4 Results of investigations for serial instruments

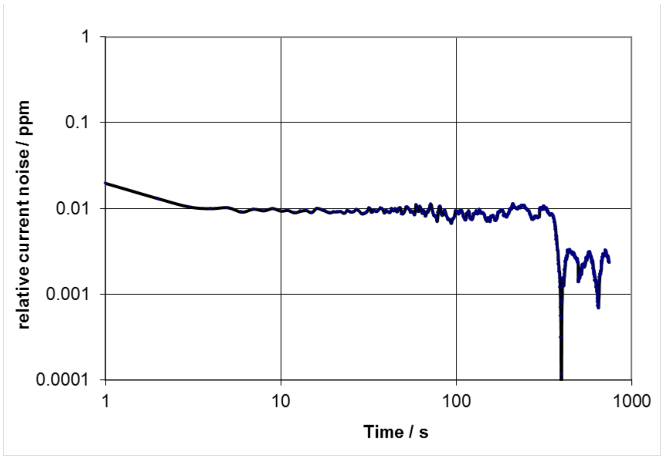

Fig.5 Allan deviation of the result of 1 mA current measurement.

III. Conclusion

Accuracy of current measurements in the range from 0.1 nA to 1 mA for non-quantum devices is limited by the shot noise. In the range above 0.1 mA Zener the voltage source can limit the accuracy at a level near 0.01 ppm. Thus, it is possible to use non-quantum sources in the range above 0.1 mA for comparisons with quantum sources at the level of 0.01 ppm.

References

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