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Calibration of low-current meters at nA level with the capacitance-charging method

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Abstract **-** The most accurate generation of dc currents in the lower ranges is performed with the capacitance-charging technique. Implementations of the method are typically limited to a maximum current in the 100 pA range. Here we present a range extender which can be employed as plug-in in existing setups. The extender permits to scale the current of a ×10 factor and reach the nA range. Results of calibration of low-current meters with and without the use of the extender.

I. Introduction

The accurate generation of low dc currents is of relevance for the calibration of low dc current meters and for research on electron-counting sources based on single-electron tunneling. Generation by Ohm's law, where a current I is generated by applying a dc voltage V on a resistor R, becomes more and more impractical for decreasing current values, for a number of reasons. The very high-valued resistance standards R to be employed have high voltage and temperature coefficients and long time constants, and poor time stability. It is difficult to achieve a proper calibration under low applied voltage. Further, the method is prone to errors caused by the voltage burden of the instrument under calibration.

In recent years, several national metrology institutes have developed low-current generators [1-7] based on capacitance charging. A linear voltage ramp $v(t) = St$, having slope S, is applied to a capacitor C, and a displacement current $I = C\,\mathrm{d}v/\mathrm{d}t = SC$ is generated. Capacitance standards have relatively low environmental coefficients, are highly stable and can be accurately calibrated; S can be calculated from readings of a high-accuracy sampling digital voltmeter. The generated current is not affected by the voltage burden of the meter under calibration, since this affects v but not its slope S.

C has to be a gas-dielectric or vacuum capacitance standard, since all solid-dielectric capacitors show the phenomenon of dielectric absorption [8] to some extent, which would severely limit the generator accuracy. Available commercial capacitors range from 1 pF to 10 nF; however, 10-nF capacitors cannot be employed in calibrations because they're likely to cause instabilities in the input circuitry of most meters [9]. Maximum $S = 2V_{\max} T^{-1}$ is limited by the maximum voltage $V_{\max}$ available by the ramp generator and the ramp duration T, which should be sufficiently long for a proper settling of the measurement system. In most published generators [2, 3, 5, 7] T ranges between 100 and 200 s, and $V_{\max} = 10$ V, which in turn limits the maximum available current to 100-200 pA when the largest C (1 nF) is employed. The method, and several implementation, have achieved mutual validation at the European level within the framework of EURAMET.EM-S24 international intercomparison [10].

We here introduce a simple range extender amplifier that permits to raise the generated current to nA level. The range extender is a voltage amplifier, which increase $V_{\max}$ to 100 V, and can be can be connected to any existing ramp generator.

II. Calibration setup

The measurement setup block schematics is shown in Fig. 1, and a photo is shown in Fig. 2. The range extender E is connected to the existing ramp generator RG (having $V_{\max} = 10$ V) [3]. The ramp voltage $v(t)$, sampled by voltmeter V (Agilent 3458A, 10 or 100 V range), is applied to the gas-dielectric capacitor C (General Radio mod. 1404-A series) and converted to a current I, measured by the meter under calibration M. Timer T clocks all instrument, which are acquired by personal computer PC. The current is computed from voltage samples with a simple finite-difference model [3]. The electrical schematics of E is shown in Fig. 3; it is based on Apex mod. PA88 high-voltage power MOSFET integrated op amp, in a standard ×10 gain configuration.

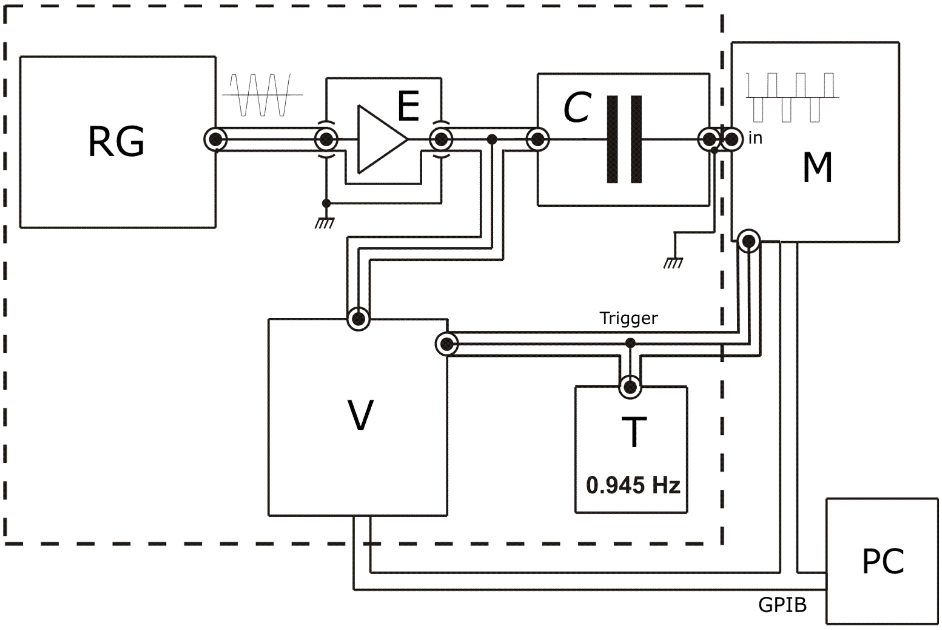


Figure 1. Measurement setup. RG is the ramp generator, E the new range extender, *C* the injection capacitance, M the meter under calibration, V the sampling voltmeter, T the clock timer which triggers V and RG, PC the data acquisition computer. The original RG has $V_{\max} = 10$ V, which is raised by E to $V_{\max} = 100$ V.

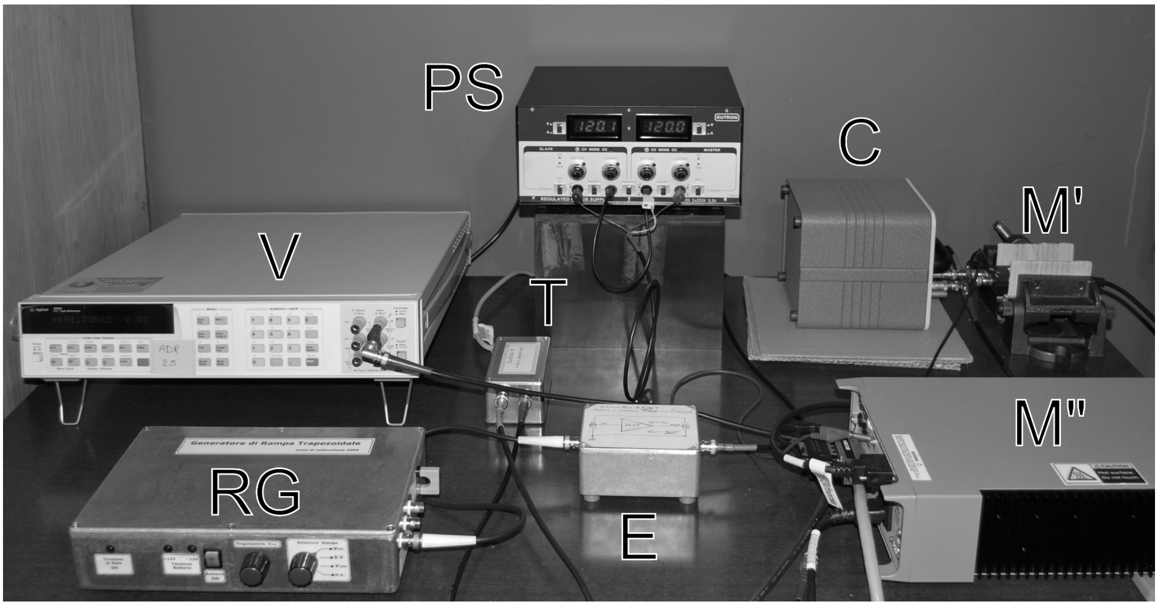


Figure 2. A photo of the measurement setup described in Fig. 1. The meter M consists of a measuring head M' (connected to C directly, without employing a cable) and a remote control and display unit M". PS is the power supply for E (not shown in Fig. 1).

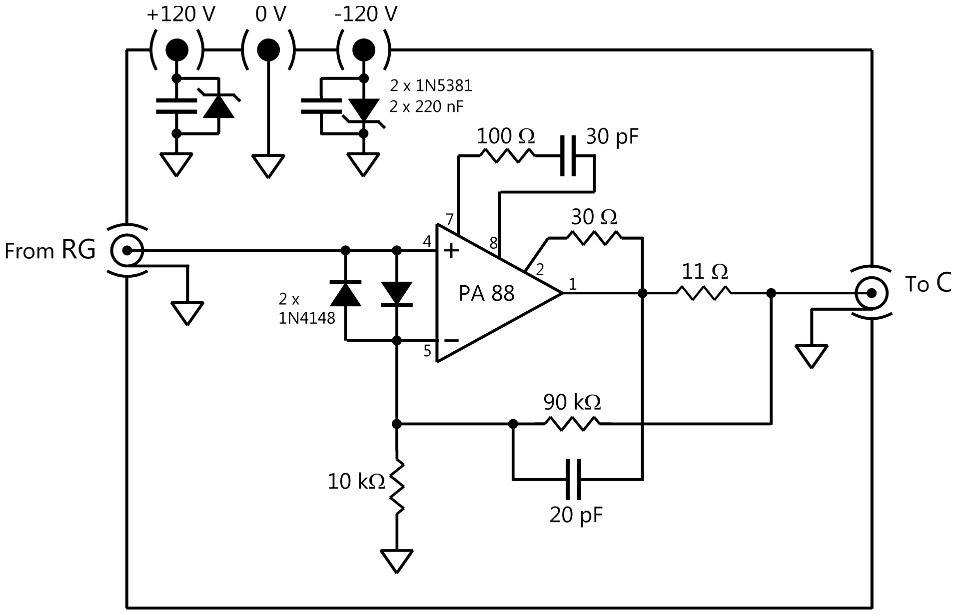


Figure 3. Electrical schematics of the range extender amplifier E displayed as a block in Fig. 1.

III. Experimental

In the calibration of a current meter M, the quantity being calibrated is the calibration factor $G = (I_\mathrm{R} - I_\mathrm{R0})/I$ where I_R is the reading when applying the reference current I, and I_R0 the reading under zero applied current. The meter of choice for all experiments performed is the Keithley mod. 6430 sub-femtoampere remote sourcemeter. All experiments are performed in an electromagnetically shielded room, thermostated at 23 ±0.5°C.

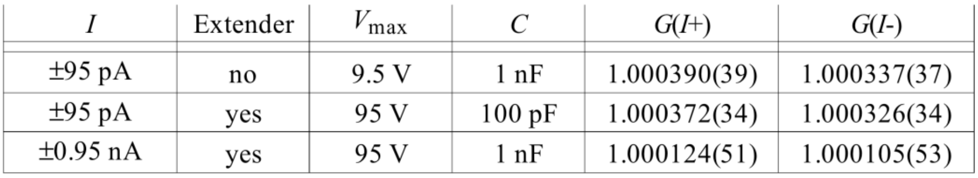
Calibrations have been performed at nominal currents near 100 pA and 1 nA (the actual values are slightly below decadic values to avoid overloading of M, which fullscale values are exactly 100 pA and 1 nA) for both positive and negative applied currents.

The uncertainty budget for calibration at 100 pA has already been given in [3]. An uncertainty budget for the generation of currents at 1 nA level is shown in Tab. 1. An important contribution is assigned to *C.* It takes into account, in a conservative way, possible frequency dependency effects, since its calibration is performed as a two-terminal pair impedance [11] at 1 kHz frequency.

Source	Uncertainty (mA A^{-1})
M resolution	<1
C	30
$v(t)$ sampling	6
Timebase	1
Current leakages	10
Reading noise	39
G	51

Tab. 1. Uncertainty budget for the calibration of M

The measured values *G* of M are reported in Tab. 2 together the corresponding measurement relative standard uncertainty. For the lower nominal current of 100 pA, a direct comparison of measurements performed with and without the range extender show full consistency.



I	Extender	$V_{\max}$	C	$G(I+)$	$G(I-)$
±95 pA	no	9.5 V	1 nF	1.000390(39)	1.000337(37)
±95 pA	yes	95 V	100 pF	1.000372(34)	1.000326(34)
±0.95 nA	yes	95 V	1 nF	1.000124(51)	1.000105(53)

Tab. 2. Results of calibration of a low-current meter M, for positive $G(I+)$ and negative $G(I-)$ current values I. Two calibrations at the same nominal current ±95 pA are performed with and without the range extender, and can be directly compared for a mutual validation.

IV. Conclusions

The results reported in Tab. 2 show that the range extender can be successfully employed to extend the range of the capacitance-voltage ramp method to 1 nA, and to improve INRIM calibration and measurement capability (CMC) on this range by reducing the present CMC uncertainty by an order of magnitude. The range extender can be easily employed as a plug-in for other ramp sources already available.

Acknowledgements

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