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Feasibility of a digital counterpart of thermal-converter-based current step up

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***Abstract* – The development of a new traceability step-up chain using digital instruments (digitisers) with direct traceability to SI would allow dynamic measurements of current and voltage waveforms. CEM has studied the feasibility of a digital counterpart for the traditional thermal-converter-based step up, which is limited to provide the RMS values of monotone signals. This paper describes and validates this new digital method, obtaining a complete set of calibrations shunt-digitizer for currents up to 1 A. The performed measurements show very promising results, comparable to the well-established thermal-converter approach results, with differences between both techniques lower than 2 μA/A up to 1 kHz.**

I. INTRODUCTION

The International System of Units (SI) base unit of electric current, the ampere, A, after the 2019 SI redefinition, is defined by taking the fixed numerical value of the elementary charge e to be $1.602\,176\,634{\cdot}10^{-19}$ when expressed in the unit C which is equal to A·s, and where the second is defined in terms of caesium frequency $\Delta\nu_{\mathrm{Cs}}$ [1].

The ampere can be realized by using Ohm's law, the unit relation A=V/Ω, and practical realizations of the SI derived units, the volt V and the ohm Ω, which are based on the Josephson and quantum Hall effects, respectively. This practical realization is widely adopted in the metrology community. As the values of the elementary charge e and the Planck constant h are fixed in the current SI, the Josephson and von Klitzing constants $K_{\mathrm{J}} = 2e/h$ and $R_{\mathrm{K}} = h/e^2$ have also fixed numerical values.

Although the traditional realization of alternating current (ac), based on the so called thermal transfer from direct current (dc) by means of thermal converters [2] and used by most of the National Metrology Institutes (NMI), allows to obtain accuracies of the order of 1 μV/V, these are limited to Root Mean Square (RMS) values not being valid for dynamic measurements, which are the kind of measurements found in the industry. Furthermore, thermal converters methods are lengthy and laborious.

A new traceability chain based on digitisers directly traceable to SI would allow to measure voltage and electric current waveforms dynamically. The inclusion of this digital traceability chain in NMIs, has to be preceded by a thorough validation.

The Spanish Metrology Centre (CEM) together with other NMIs have been working on this topic for some time: from the characterization of analog-to-digital converters (ADC) [3-5], to the description of quantum standards [6-9] and the combined use of ADC and quantum standards on the same measurement arrangement [10-14].

The research in this paper is divided into two sections. The first section (section II) presents the measurement setup and results of a digital counterpart of the traditional thermal-converter-based step up, using a combination of shunts and digitisers in the ranges 20 mA - 1 A, and 10 Hz - 10 kHz. This digital counterpart can be directly traceable to the SI definition. The second section (section III) includes the measurement setup and results for the validation of the new digital traceability chain. This chain is validated by comparing the measurements against historical thermal-converters-based step up data.

The measurements obtained in this paper show comparable results to the well-established thermal-converter approach for currents up to 1 A when the frequency is lower than 1 kHz.

II. DIGITAL-BASED CURRENT STEP UP

A. *Theory*

The digital based current step up method consists in providing the same series current to two combinations of shunt-digitiser connected in parallel: the shunt-digitizer under test and the standard shunt-digitiser (Figure 1). The output voltage of the shunts is sampled independently and simultaneously by each digitiser.

By comparing these outputs and knowing the correction of the standard shunt-digitiser (calibrated against Josephson voltage standard), the correction of the shunt-digitizer under test can be known. Repeating this process with higher current shunts, and taking the calibrated combination of shunt-digitizer under test as the standard combination of shunt-digitiser for the next step, a complete digital traceability chain can be established.

B. *Measurement setup*

The measurement setup for the 20 mA to 50 mA step is represented in Figure 1, where two digitisers Keysight

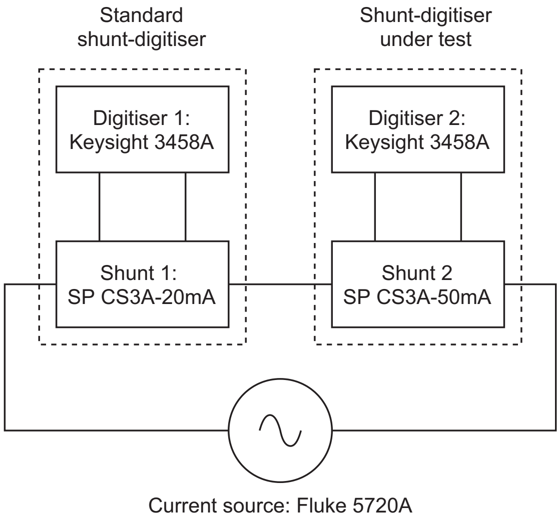

Fig. 1. Setup of the digital step up.

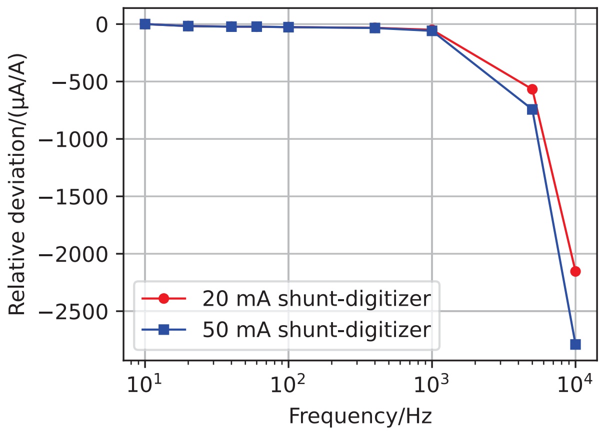

Fig. 2. Frequency response normalized with 10 Hz *response for the* 20 mA *to* 1 A *step up.*

3458A and a current source Fluke 5720A working in voltage mode are used. Further setup information regarding noise reduction, shielding and guarding can be found elsewhere [15].

The same setup and procedure have been used to step up from 20 mA to 1 A in five steps. Nine frequencies, from 10 Hz to 10 kHz and dc have been considered. The aperture time (T_a) during which digitisers are reading the current signal is 200 µs up to 100 Hz. Aperture time decreases for higher frequencies since it is limited by the necessary sampling frequency. Further details about selected parameters can be found in Tables 1 and 2.

An in-house developed software based on four parameter sine-fitting has been used for processing the digitised data [16].

C. *Measurement results*

Regarding the first step up (20 mA - 50 mA), Figure 2 represents shunt-digitiser frequency responses. The values has been represented as the relative deviation from the values at 10 Hz, therefore, the quantity unit is µA/A.

Responses include the contribution of both, shunts and digitisers.

D. *Discussion*

Figure 2 shows that the normalized frequency response has a moderately constant value up to 1 kHz. For higher frequencies, differences are much bigger.

The frequency response is mainly due to the digitizers, as obtained in a previous work [10].

The main reason for the variation of the frequency response is due to the input impedance of the digitiser. Also, at higher frequencies the aperture time must be lower, which means lower accuracy and higher noise on the measurements.

As stated previously, by knowing the response of the 20 mA shunt-digitizer combination it is possible to obtain the response of the 50 mA combination one.

III. VALIDATION

A. *Theory*

The validation can be achieved comparing shunt ac-dc differences obtained by thermal and digital methods. To remove the digitizer influence, two set of measurement are needed: one with the configuration shown in Figure 1 and another swapping digitisers.

Contrary to thermal-converters-based realizations of ac current, for a digital-based step up of shunts, dc measurements are not required. However, in this validation dc measurements are performed since the traditional thermal converters approach provides just ac-dc difference.

The diagram on Figure 3 represent schematically the relationship between inputs and outputs (in general, currents or voltages) of combinations of shunt-digitiser. For narrow input ranges, the relationship can be represented by two parallel straight lines, one for ac (upper line, in blue) and the other for dc (lower line, in green). Considering the setup shown in Figure 1, the following steps are taken:

1. ac current is applied to the standard shunt-digitiser and shunt-digitiser under test. The output of both digitisers is recorded at the same time.

2. dc current is applied to the standard shunt-digitiser and shunt-digitiser under test. The output of both digitisers is recorded against the same time.

3. ac-dc measurement differences (δ_s and δ_t) are calculated substracting recordings from step 2 to record-

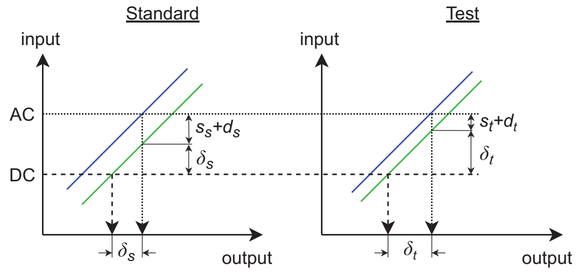

Fig. 3. Diagram of the validation method.

ings from step 1. Sub index s refers to the standard equipment and t to the equipment under test.

Considering a unitary slope of the ac and dc response of shunt-digitiser combinations, the following system of two equations can be written:

$$\begin{cases} AC_1 = DC_1 + \delta_s + (s_s + d_s) \\ AC_1 = DC_1 + \delta_t + (s_t + d_t) \end{cases} \tag{1}$$

Where s is the difference ac-dc of the shunt and d is the difference ac-dc of the digitiser. AC and DC are the input magnitudes which, in the general case, can be voltage or current. Note that the key factor here is that the input to both combinations of shunt-digitiser is the same, and that combining the equations from system 1, AC and DC dependency is removed:

$$\delta_s + (s_s + d_s) = \delta_t + (s_t + d_t) \tag{2}$$

If digitisers are swapped, and considering that ac-dc difference of shunts and digitisers (s_t, s_s, d_t and d_s) are the same after the swap, since applied current has always a similar level and measurements are taken in a short period of time, the following system of equations can be written:

$$\begin{cases} AC_2 = DC_2 + \delta'_s + (s_s + d_t) \\ AC_2 = DC_2 + \delta'_t + (s_t + d_s) \end{cases} \tag{3}$$

And analogously to equation 2:

$$\delta'_s + (s_s + d_t) = \delta'_t + (s_t + d_s) \tag{4}$$

Combining equations 2 and 4, the next expression is achieved:

$$(s_t - s_s) = \frac{(\delta_s + \delta'_s) - (\delta_t + \delta'_t)}{2} \tag{5}$$

From where the difference between test and standard shunts ac-dc difference, $(s_t - s_s)$, can be obtained, since digitiser influence is removed.

This value will be compared to the one obtained by thermal converter characterization.

B. Measurement setup

Two set of measurements are taken here. For the first one, the results of section II are used providing that dc measurements, with its respective aperture times, are also performed.

For the second set of measurements, the digitisers are swapped, and the same procedure described in section II.B is followed. As well, dc measurements have to be included.

C. Measurement results

Table 1 shows the numerical values of $(s_t - s_s)$, described in section III.A, for the first step up (20 mA - 50 mA). The analogous quantity due just to the contribution of digitisers, $(d_t - d_s)$, is also included for comparison purposes. It was calculated subtracting equation 4 from equation 2.

Table 2 includes the equivalent historical results for a thermal-converters-based realization of ac current [16] together with the results of the digital step up (extension of Table 1) and the differences between both techniques. In the thermal converters columns, blank spaces indicate that, for certain frequencies, there are not historical results .

Table 1. Numerical values of the difference between test and standard shunts ac-dc difference, $(s_t - s_s)$, described in section III.A for the step up 20 mA *to* 50 mA.

f/Hz	T_a/µs	$(s_t - s_s)$/(µA/A)	$(d_t - d_s)$/(µA/A)
10	200	-0.3	-0.9
20	200	-0.2	-1.1
40	200	-0.5	-0.5
60	200	-0.2	-0.5
100	200	0.2	-1.2
400	140	-0.8	0.6
1 000	60	-1.9	7.8
5 000	12	-20.3	164.8
10 000	12	-69.4	631.1

D. Discussion

$(s_t - s_s)$ in Table 1 shows a similar performance to the frequency response represented in Figure 2, with very low differences (lower than ±2 µA/A up to 1 kHz). Also, $(s_t - s_s)$ is lower than $(d_t - d_s)$, especially for higher frequencies. This result is expected, since the influence of ac signals in complex devices as digitisers is higher than the influence of ac signals in relatively simple low reactance devices as shunts.

Table 2 shows very small differences for the $(s_t - s_s)$ of the thermal converter step up approach, as expected. This is true for the whole range of currents and frequencies (the higher discrepancy is -2.4 µA/A at 10 Hz for the 200 mA to 500 mA step up).

Table 2. Difference between test and standard shunts ac-dc difference, $(s_t - s_s)$, for the equivalent historical results of a thermal-converters-based realization of ac current, the digital step up measured in this paper and the differences between both techniques.

	Thermal converters step up $(s_t - s_s)/(\mu A/A)$					Digital step up $(s_t - s_s)/(\mu A/A)$					Techniques difference (μA/A)				
Step up /mA → / f/Hz ↓	20 - 50	50 - 100	100 - 200	200 - 500	500 - 1000	20 - 50	50 - 100	100 - 200	200 - 500	500 - 1000	20 - 50	50 - 100	100 - 200	200 - 500	500 - 1000
10	-2.2	-1.8	-2.0	-2.4	-1.7	-0.3	0.6	0.5	1.2	1.7	1.9	2.4	2.5	3.7	3.4
20	-0.6	-0.7	-0.1	-0.9	0.0	-0.2	0.6	0.7	1.4	0.5	0.4	1.4	0.8	2.3	0.5
40	-0.6	0.0	-0.5	0.0		-0.5	0.5	1.1	1.4	1.0	0.0	0.5	1.6	1.5	
60	0.0	-0.1	0.0	-1.3		-0.2	0.0	0.5	0.9	1.4	-0.2	0.1	0.5	2.2	
100	0.1	-0.1	-0.1	0.3		0.2	0.4	0.7	1.1	0.5	0.1	0.5	0.9	0.8	
400	0.8	0.2	0.2	0.2		-0.8	0.9	2.0	0.3	0.3	-1.6	0.8	1.8	0.1	
1 000	0.0	0.2	0.0	-0.1	0.0	-1.9	-0.6	-0.8	0.5	0.4	-1.9	-0.9	-0.8	0.6	0.5
5 000	0.7	0.9	0.1	-1.4		-20.2	4.9	5.7	-2.1	5.7	-20.9	4.1	5.7	-0.6	
10 000	-0.7	1.4	-0.1	-1.3	-0.6	-69.4	12.7	17.1	-4.2	12.5	-68.7	11.3	17.2	-2.9	13.1

In the case of the digital step up, $(s_t - s_s)$ is also very low for the whole current range when the frequency is lower than 1 kHz. In this instance, the maximum discrepancy is 2.0 μA/A at 400 Hz for the 100 mA to 200 mA step up.

Regarding frequencies between 5 kHz and 10 kHz, some differences are also very low, however, this does not occur for all the step ups: some step up differences present moderately high positive values, others present high negative ones, showing high variability for higher frequencies.

The data from the difference of both techniques shows small differences up to 1 kHz for all step ups. This means that, knowing the digitiser error from a quantum calibration, equivalent results to thermal converter can be achieved with the advantage of not performing dc measurements and with the possibility of dynamic measurements analysis.

IV. CONCLUSION

This paper explains how to perform a digital based current step up using a combination of shunts and digitisers. The measurements obtained using this method show very good results, comparable to the well-established thermal-converter approach results: differences of less than ±2 μA/A between both techniques. This is true when the current ranges from 20 mA to 1 A and when the frequency is lower than 1 kHz. For these ranges the technique could be considered as validated. For bigger frequencies deviations get higher and, therefore, accuracy is limited.

Although, compared to the thermal converter method, the bandwidth of the digital method is narrower, it provides important advantages. The promising results described here will allow NMIs to establish a digital traceability chain for ac current in the near future, allowing high accuracy dissemination for complex waveforms that vary with time or have a decent amount of harmonic content. At the same time this digital chain will simplify and shorten calibration procedures.

V. ACKNOWLEDGMENT

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