Voltage-Ratio Calibration System up to 50 kHz

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Abstract. This paper describes a voltage-ratio measuring system that can be used up to 50 kHz with high accuracy. It is based on two Keysight 3458A digital multimeters, working in DCV sampling mode. An external trigger based on a rubidium clock, drives both digital multimeters. It is applied to the calibration of a set of voltage dividers with primary voltages from 4 V to 1024 V.

1. Introduction
A project to design and construct a reference system for measuring voltage, current and power, up to 100 kHz, is been running [1], [2]. This project is being jointly developed by the National Metrology Institutes of Argentina (Instituto Nacional de Tecnología Industrial (INTI)), Brazil (Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO)) and Uruguay (Administración Nacional de Usinas y Transmisiones Eléctricas (UTE)). The objective is the construction of three measuring systems, one for each institute. This project will contribute to provide calibration services in measuring ranges still not covered by these institutes. The project will also contribute to improve the traceability not only of electric power but also of related quantities like ac-dc transfer, voltage ratio, phase angle, ac voltage and ac current.

For the voltage input, this standard system requires voltage dividers to scale the input values (4 V to 1024 V) to the value allowed by the analogue-to-digital converter (0.8 V) [3], [4]. The motivation for the present work comes from the need of calibration of these dividers.

Different methods can be used to calibrate this type of dividers. One of them is to compare the divider under test against an ac-dc thermal converter, other to measure the step response [5], [6], and third, to perform a step-up test, as described in the next section. For this last one, it is required a measuring system that can compare the output voltages of the two dividers under test.

Previous developments of a low-frequency power-quality meter [7], [8] based on two Keysight 3458A digital multimeters (DMM) [9] allowed to perform step-up calibrations for voltage dividers up to 5 kHz. In this work, an extension of that method, that reaches 50 kHz, is described. This method measures the amplitude and the phase-displacement differences between the two voltages to be compared.
2. Step-up method
The set of dividers includes the following nominal input voltages: 4 V, 8 V, 16 V, 32 V, 64 V, 128 V, 256 V, 512 V and 1024 V. The nominal output voltage is 0.8 V and the output impedance is 200 Ω, for all dividers.

The step-up method consists in comparing two adjacent dividers up to the voltage of the lower one. As the ratio between them is 2:1, the output voltages to be compared will be up to 0.8 V and 0.4 V. One of the dividers reaches its nominal voltage, but the other reaches only half of its nominal voltage. Therefore, this method requires the characterization of the voltage linearity of each divider. As in this case, the non-linear behaviour is mainly due to temperature variation, a low-frequency or dc test is enough for that. This ratio variation against the applied voltage is considered for correcting the step-up data.

If dividers with equal nominal voltage are compared, the ratio between them is 1:1 and equal voltages are measured by the calibration system. Then, this particular application of ratio calibration of this set of dividers implies only two ratios, 1:1 and 2:1.

3. Calibration system
The voltage ratio calibration system comprises two DMMs [9], whose inputs are connected to the voltages to be compared. They work in DC Direct Sampling mode. To be able to digitize signals up to 50 kHz, the DMMs are configured with a small aperture time of 1.4 µs. With this aperture, the resolution is limited to 16 bits [9]. Both DMMs are synchronized in parallel by a function generator [10] using a TTL signal of 100 kHz. The function generator is driven by a rubidium clock to reduce jitter [11]. A block diagram of the voltage-ratio calibration system is shown in figure 1.

![Figure 1. Block diagram of the voltage-ratio calibration system.](image)

The 1-V range is used in both DMMs. The program runs the configuration software and reconstructs the digitized signals using Interpolated-Fast-Fourier-Transform (IFFT) techniques to get the amplitude ratio and phase difference. A Hanning window of the length of the original vector to be analysed was used. Then, Discrete-Fourier-Transform is performed, analysing the spectral leakage. With this information, the frequency of the signal is calculated allowing to compute modulus and angle of the original vector.

There is no synchronization between the input signals of the DMM and the sampling frequency. Each DMM runs at its internal 10 MHz clock. The acquisition times of the samples are around 0.7 s. Even very small differences between clocks, of few parts in 10^6, ensure asynchronous sampling, so that random points are sampled in each burst.

The configurations of commands of both DMMs are sent sequentially, so that one DMM is ready to measure before the other. The trigger control module enables the arrival of the pulses to the external trigger inputs of both DMM only when both DMMs are ready. The enabling and disabling of pulses is done by the software.

Before starting a ratio measurement, the system is adjusted to the ratio value that will be used. If the ratio is 1:1, the same voltage signal is applied to both DMMs. If the ratio is 2:1, a standard
inductive divider 2:1 ratio is used to compensate for scale errors. In this way, most error sources are compensated.

3.1 Multimeter error sources
We consider five different influence factors on DMM errors when operating in DCV sampling mode at 1-V range [12], [13]: linearity, aperture time, dissipation factor of the input divider, input low-pass filter, and time differences of external trigger.

Linearity error in the 1-V range was studied in dc voltage, and this value is around some parts in $10^6$. It is necessary to make a correction for the aperture time in amplitude and phase. This is done using equations (1) and (2).

$$Aperture\ Amplitude\ Correction = \frac{\sin(\pi f \times Taper)}{\pi f \times Taper}$$  \hspace{1cm} (1)

$$Aperture\ Phase\ Correction = \frac{1}{2} Taper \times f$$  \hspace{1cm} (2)

where $Taper$ is the value of the aperture time, and $f$ the frequency. The errors that these factors compensate are low at low frequencies, but increase at high frequencies. For 50 Hz, the amplitude error is lower than $10^{-6}$, but it is about $8000 \times 10^{-6}$ at 50 kHz. Phase error is linear with frequency, and reaches 35 000 $\mu$rad at 50 kHz. This means that even applying the correction factors, significant uncertainties can exist due to the uncertainties in $Taper$ and $f$. Nevertheless, as only the difference between both DMMs is relevant, the influence of this error source can be significantly reduced performing the previous adjustment with the standard divider.

The DMM input impedance cause some errors in the voltage measurements. For the 1-V dc range, the nominal value is 1 M$\Omega$ with 140 pF in parallel. The influence of the input resistance is constant with the frequency, but the dissipation factor of the capacitance reduces the effective DMM input resistance at high frequencies. Both resistances result in parallel with the output resistance of the divider, attenuating the signal. The input impedances of both DMMs were measured with a RLC bridge. Figure 2 shows the values of the parallel capacitance ($C_p$) and parallel resistance ($R_p$) against frequency.

![Figure 2. Parallel capacitance ($C_p$) and parallel resistance ($R_p$) against frequency of both DMMs.](image-url)

The influence of this factor depends on the impedance of the voltage sources to be compared. In case of the voltage dividers previously mentioned, all of them have output resistance of 200 $\Omega$. With this impedance the error caused by the input resistance of the DMM is -200 $\mu$V/V at low frequency, and it increases with frequency, up to -250 $\mu$V/V at 50 kHz because of the dissipation factor of the
input DMM capacitance. However, taking into account that the input impedances of both DMM are nearly equal, the ratio error for this effect is practically compensated.

The input capacitance with the output divider resistance produce a linear phase shift with frequency around 10 000 µrad at 50 kHz, but as both DMMs have similar capacitance, this influence in ratio measurements is reduced to less than 600 µrad.

This DMM type has a low-pass filter at its input with nominal cut-off frequency of 150 kHz. The amplitude and phase error generated by this filter is evaluated by equations (3) and (4).

\[ \text{Bandwidth Amplitude Error} = \frac{1}{\sqrt{1 + \left(\frac{f}{\text{bandwidth}}\right)^2}} \]  
\[ \text{Bandwidth Phase Error} = \tan^{-1}\left( \frac{f}{\text{bandwidth}} \right) \]  

Corrections using these equations work very well at low frequencies, but near the cut-off frequency, the amplitude and phase errors are very large. They reach around 15% y 20° at 50 kHz. Even taken into account that in ratio measurements errors are similar for both DMMs, the compensation is not perfect and an excessive residual error remains. It is necessary to measure the actual bandwidth of each DMM for correcting the results. We found 129.854 kHz and 130.132 kHz for the tested units. Additionally, all these error sources, as trigger systematic differences, can be evaluated in the system calibration test with the inductive voltage divider, and discounted from the measurement results. Anyway, drifts and random variations after calibration change the correction factors generating errors that cannot be compensated. They were evaluated by analysis on experimental results, as shown in the following section.

3.2 Experimental results
A preliminary test was done applying to both DMM inputs the same signal (0.7 V rms). Table 1 shows the results. The uncertainty columns refer only to type-A uncertainty (expanded, k=2), averaging 20 measurements.

| Frequency (kHz) | Modulus (×10⁻⁶) | Phase (µrad) | Uncertainty (modulus) (×10⁻⁶) | Uncertainty (phase) (µrad) |
|----------------|-----------------|-------------|-------------------------------|---------------------------|
| 1              | -22.4           | 0.3         | 0.3                           | 0.8                       |
| 10             | -33.3           | 10.9        | 0.6                           | 3.8                       |
| 20             | -35.8           | 21          | 1.5                           | 6.8                       |
| 30             | -35.2           | 59.6        | 2.1                           | 8.7                       |
| 40             | -18.0           | 92.8        | 3.5                           | 15.3                      |
| 50             | 34.0            | 179.5       | 3.5                           | 13.8                      |

These values show that the DMMs are adequate stables and the method has acceptable error and dispersion for the objective of this work. Additional tests on ratio 2:1 are being performed.

4. Conclusions
A measuring system for voltage ratio measurements has been presented, reaching frequencies up to 50 kHz. It is based on two high precision multimeters which are synchronized by a high stable external
5. References
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trigger. Experimental results at ratio 1:1 show errors around $40 \times 10^{-6}$ in modulus and 20 µrad in phase displacement, at 20 kHz. At 50 kHz, phase error increase, up to 180 µrad, but still the system is suitable for many ratio measurements applications.