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Wideband resistive voltage divider for a standard wattmeter

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Abstract. This work shows the state of development of resistive voltage dividers for use in a standard wattmeter that covers a frequency range from 50 Hz to 100 kHz. The voltage ranges go from 4 V to 1024 V with an expected accuracy of 20 µV/V and 60 µrad/kHz. Nonlinear influences are studied and different methods to compensate the effect of stray capacitances are analysed, as well as the measurement systems used to calibrate these devices.

1. Introduction

The amount of nonlinear loads in power networks has been increased during the last decades. This leads to distortion in currents and voltages which can disturb communication and control systems, as well as other electronic devices connected to the network. We are running a project [1] for designing and constructing a reference system for measuring electric voltage, current and power up to 100 kHz.

This project is being jointly developed by the National Metrology Institutes of Brazil, Argentina and Uruguay (Instituto Nacional de Metrologia, Qualidade e Tecnologia (Inmetro) in Brazil, Instituto Nacional de Tecnología Industrial (INTI) in Argentina, and Administración Nacional de Usinas y Transmisiones Eléctricas (UTE) in Uruguay). 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 from 4 V to 1024 V, to the voltage value admitted by the analogue to digital converter (0.8 V). It is not easy to design such dividers with very low error at the highest frequency. There are parasitic capacitances and inductances that produce changes in the voltage ratio in amplitude and in phase, which have also been studied in other electrical fields [2]. Among this, the resistors and isolating materials used in the divider have nonlinear losses, which lead to nonlinear behaviours that cannot be compensated under distorted voltages. The following sections show the progress in the development of these dividers.

2. General requirements

To cover all ranges (from 4 V to 1024 V), nine resistive voltage dividers will be used, one at a time, with binary nominal ratios. Table 1 shows details. The input resistance and the dissipated power depend on the input voltage. For all cases, the output resistance is 200 Ω and the output voltage is 0.8 V.

Table 1. Characteristic details of the set of the dividers.

Input voltage (V)	Ratio	Input resistance (kΩ)	Power (W)
1024	1280	256	4.10
512	640	128	2.05
256	320	64	1.02
128	160	32	0.51
64	80	16	0.26
32	40	8	0.13
16	20	4	0.06
8	10	2	0.03
4	5	1	0.02

In this way, the nominal current is constant for all dividers (4 mA at nominal voltage). The ratios were selected with binary ratios to allow the calibration against a standard binary inductive voltage divider [3] at low frequencies, and for covering the whole voltage range with the same step-ratio between each adjacent pair. The input arms are constructed with multiple individual resistors in parallel-series connection to limit the power of each one at 100 mW. Nonlinear effects and stray capacitances will be discussed in the following sections.

3. Linearity

To get high accuracy in all ranges of voltage and frequency, it is necessary that the divider behaves as a linear device. If the voltage waveform is distorted, as can be in this project, nonlinearities mean that it is not possible to correct the response in a general way for an arbitrary harmonic content. On the opposite, in linear circuits a correction can be done according to the sweep frequency response analysis or the step response.

In voltage dividers the most important nonlinear effect is dielectric losses. High electric fields through isolation material can cause power losses that vary with frequency and field intensity in a nonlinear way. Other nonlinear effects, such as skin effect, can be neglected in this application. The main components of the divider that contribute to nonlinear effects are resistors, printed circuit board (PCB) and capacitors used for compensation and guarding [4]. In resistors, the larger contribution to nonlinearities is caused by their isolation covers due to dielectric losses. In some models it is possible to remove the cover, and for others, the manufacturer can deliver special units without cover (see figure 1). This last option was applied in this work, and tests confirm the behaviour improvement. A resistor (Vishay Z-Foil type) of 10 kΩ, 0.6 W, was tested with and without cover, mounted in FR-4 PCB, PTFE PCB or mounted in air, without any PCB.

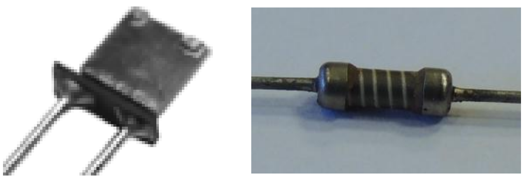

Figure 1. Resistors without cover.

The variation of the modulus of the impedance against the frequency is shown in Table 2. The values are expressed in parts in 10^6. The test was done using an ac-dc standard thermal transfer [5].

Negative values of the second and third columns mean that the ac impedance is smaller than the dc resistance. Dielectric losses cause this behaviour because they can be modelled as a resistor in parallel with the resistor under test. As these types of losses increase with frequency, the ac-dc difference also increases. The absolute values of the third column are lower than those of the second one because the PCB losses were eliminated. For this test the resistor was mounted in air, directly fixed to the measuring structure, without any PCB.

Table 2. Variation of the modulus of the resistor impedance with resistors with and without cover using different types of PCBs. Values are expressed in parts in 10^6.

f (Hz)	With cover, with FR4 PCB	With cover, without PCB	Without cover, without PCB	Without cover, with PTFE PCB
53	2	-2	3	2
1000	2	-1	1	1
10000	-8	-7	5	2
50000	-39	-28	15	8
100000	-77	-50	22	23

The fourth column corresponds to a resistor without cover also mounted in air. In this case, results show that all main nonlinear effects were eliminated and the apparent impedance increased with frequency due to stray capacitances to ground. Part of the input current was shunted to ground without passing through the thermal converter. Fifth column corresponds to resistors without cover mounted in PTFE PCB which has low dissipation factor at high frequency. The ac-dc differences are similar to column four, which shows that the dielectric dissipation of the PTFE PCB can be neglected. As a conclusion, the dividers are constructed using PTFE PCBs and resistors without covers.

4. Capacitance compensating methods

Once nonlinear effects have been eliminated, stray capacitances are the most relevant linear parasitic effect. There are some methods to compensate for stray capacitances. In coaxial structures, the capacitance to ground is generally larger than the parallel capacitance that resistors have. For compensation, one simple technique consists in adding parallel capacitors to the input and output arms, in order to have the same time constant in both arms. Although this works well in low precision dividers, it is not easy to use in high precision dividers. The capacitors have dielectric losses and stray inductances that significantly affect the ratio at high frequencies.

Other proposal to compensate ground capacitances consist in connecting a capacitive guard arm [4] with the same partial potentials than the principal arm. This technique reduces radial electric fields, but it is difficult to get a shield shape to avoid edge effects. A third compensation method is shown in figure 2. It uses a partial shield connected to the high potential terminal (right), adding a capacitance between the resistor and that terminal. Adjusting the length of this shield, it is possible to compensate the response to get an almost flat response in all the frequency range.

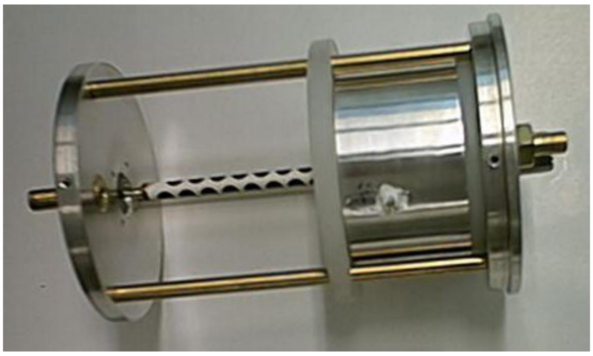

Figure 2. Adjustable partial shield to compensate for ground stray capacitances.

Although this technique has worked well for thermal transfer applications, one drawback is that it does not eliminate radial electric fields at the surface of the resistor. So that, some nonlinear losses can remain due to these fields.

In this work we explore a different shielding technique with the aim of nulling radial electric fields. Two symmetric cone-shaped electrostatic shields are installed at each end of the resistor to get null radial electric field at the whole surface of the resistor (see figure 3). The dimensions of these shields were determined using an electric-field-simulation software.

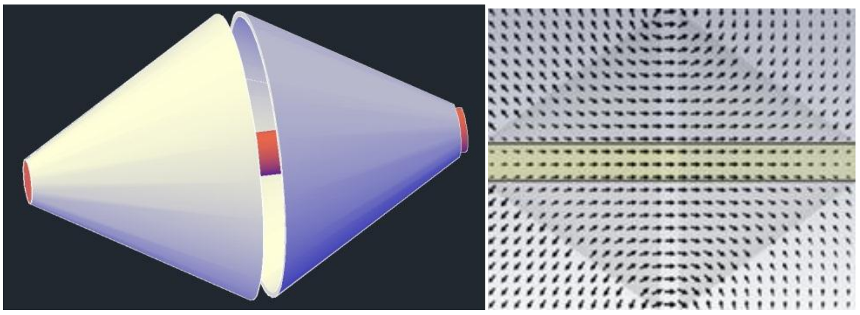

Figure 3. Electrostatic shield to null radial electrical fields. Shape and vector field diagrams.

5. Construction

A prototype of 120 kΩ was constructed. The cones are copper made and fixed to the external structure with an isolating ring between them. Inside, the PCB of the input resistor is fixed to the cones using two screws at the ends. These screws allow a small adjustment in the position of this resistor to compensate for asymmetries of the shields and for the time constant of the output resistor (200 Ω with a parallel capacitance of 15 pF), which is externally connected. Figure 4 shows a photo of the prototype without the external cylindrical cover.

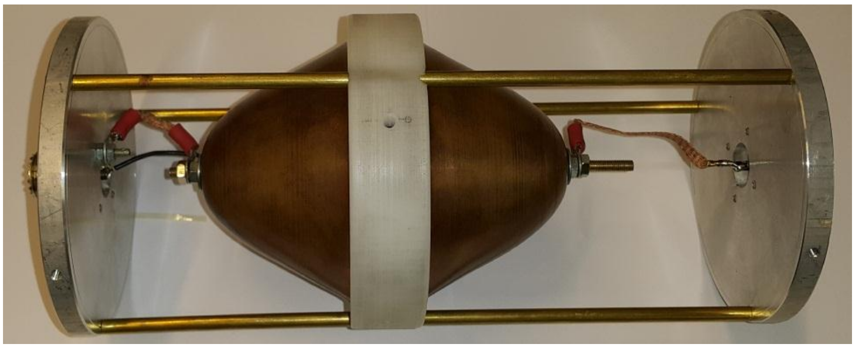

Figure 4. Construction details of the prototype.

6. Calibration

Two methods are used to calibrate the dividers. One of them compares the divider under test against a standard ac-dc thermal converter to get the modulus of the ratio error. The other method, based on the step response, gives the phase angle error.

6.1. AC-DC Method

To test the variation of the modulus of the voltage ratio when the frequency is varied between 50 Hz and 100 kHz, the dividers is compared against a standard voltage thermal converter. Figure 5 shows the ac-dc differences for the prototype. The uncertainty goes from 16 µV/V to 23 µV/V, k=2. The ac-dc variation was of 10 parts in 10^6 for the whole frequency range, so that these values are lower than the measurement uncertainty.

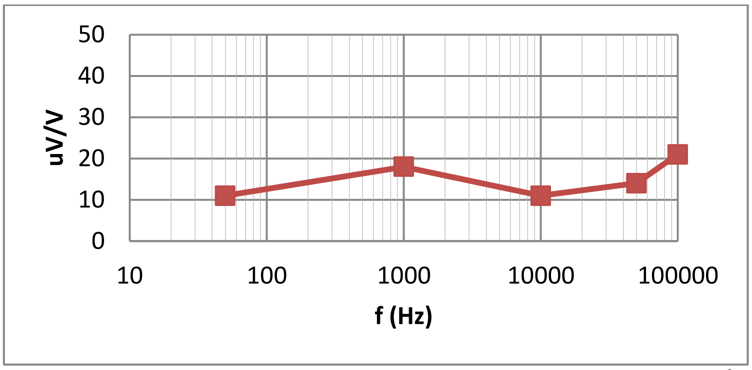

Figure 5. AC-DC differences of the prototype in parts in 10^6.

6.2. Step response

The step response method consists in applying a very fast step voltage at the input of the divider, measuring the output voltage waveform. This is a well-known technique for linear devices. As nonlinear effects were practically eliminated, this method can test modulus error as well as phase shift [6]. But, as the uncertainty of this method is generally greater than the ac-dc-method for modulus, it was only used for the calculation for the phase shift. The operational response H(p) of the divider can be expressed as

$$H(p) = \frac{1+a1.p+a2.p^2+a3.p^3+\cdots}{1+b1.p+b2.p^2+b3.p^3+\cdots} \tag{1}$$

If the excitation is sinusoidal, the complex variable p becomes $j\omega$, and at medium frequencies the higher order terms can be neglected. Then

$$H(j\omega) = \frac{1+j\omega.a1-\omega^2.a2}{1+j\omega.b1-\omega^2.b2} \tag{2}$$

For small phase displacement δ, its values is approximately

$$\delta \approx \omega(a1 - b1) \tag{3}$$

This value can be evaluated from the step response from the calculation of integral T defined as:

$$T = \int_0^{\infty}\big(1 - g(t)\big)dt \tag{4}$$

were

$$\delta \approx -\omega T \tag{5}$$

To generate the step voltage, a dc current source is connected to the input of the divider and a mercury-wetted-relay is used to short-circuit this point to ground [7]. The transition to zero has a very short time, lower than 1 ns. A 10 bits 400 MHz digital oscilloscope records the output voltage which is processed by software that computes T, calculating δ in function of frequency [6].

Figure 6 shows the response of the tested prototype. In this case, T=-0.4 ns with an uncertainty of 0.8 ns, k=2. This leads to δ=250 µrad ±500 µrad, k=2 at 100 kHz.

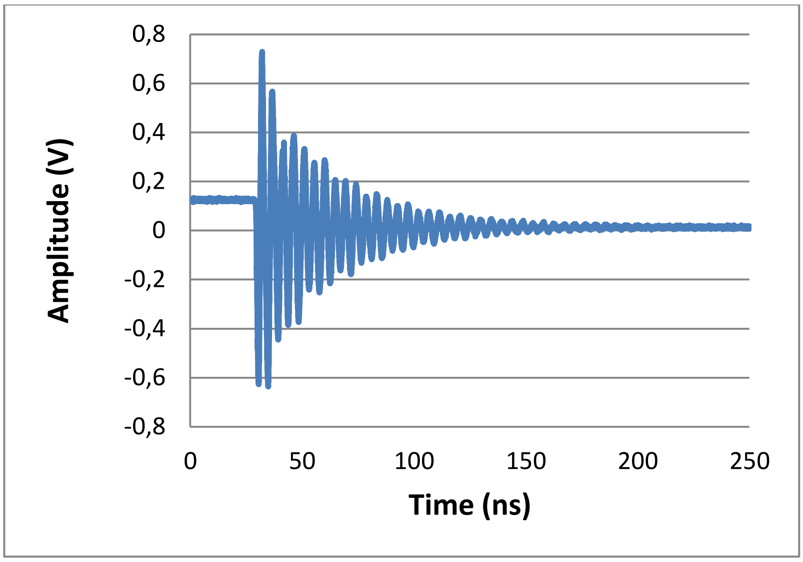

Figure 6. Step response of the prototype.

7. Conclusions

Methods to design and test resistive dividers have been proposed. They are intended for voltages up to 1024 V and frequencies up to 100 kHz. To get high accuracy, special resistors are used with very low non-linear effects and very high stability. Tests on a prototype shows an a ac-dc difference of (20±23) parts in 10^6 and a phase shift of (250±500) µrad at 100 kHz.

Acknowledgments

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