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Traceability for accurate resistive dividers

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***Abstract* – Resistive dividers find application in instrumentation because they allow fast and precise scaling-down of the applied signal input to an appropriate level of the processing electronics. Furthermore, among the applications where both wideband and accuracy requirements are demanding, resistive dividers employed as fixed-voltage ratio standards are widely used. Recently, at INRIM, coaxial voltage dividers suitable to be used in specific tasks of EU and National co-founded projects have been developed. Series-parallel type of dividers have been studied and built. Besides, methods for adjusting and calibrating their ratio, frequency response and phase difference have been analysed and experimented. Some aspects of the developed traceability chain and some examples of calibration results are given.**

I. INTRODUCTION

Analog or digital electronic systems [1], [2] generally operate at a voltage level of some volts, or even less, while the voltage signals to analyze can be even of some hundreds volts, so dividers are used to relate these two levels. Inductive dividers, widely used in the acoustic frequency range [3], have the advantage of an intrinsic accuracy defined by their turn ratio. They can have a very high accuracy especially for power frequency and around 1 kHz [4], [5]. On the other end, they do not allow dc voltage components. Furthermore, their input admittance at power frequency, can be not negligible.

Recently, at INRIM, some projects* have underlined the importance of dividers and the need for their traceability. These projects concern specifically:

- the constructions of a three-phase power analyzer and the relative scaling-down input structure for voltage and current quantities;
- the improvement of analog output electronics of a high frequency spectral purity dual polyharmonic synthesizer where the signals at the level of about 1 V have to be amplified.

Wideband inductive dividers have been taken into consideration elsewhere [6]. In such devices, in order to have a good ratio standard, all the sections of the divider should have the same electrical parameters, which is not always possible, especially at high frequencies.

Recently, resistive dividers have been taken into consideration. They have been considered in the design of attenuators in different forms such for example [7], [8]. For project under development at INRIM some models of resistive dividers have been analyzed, built and tested. However, to use them for metrological purpose their traceability has to be carefully studied and defined in each step.

II. RESISTIVE DIVIDERS UNDER DEVELOPMENT IN THE INRIM PROJECTS

Resistive dividers play an important role in two projects that have been recently undertaken at INRIM.

In the first project, a system for the accurate characterization of wide-band wattmeters, power quality analyzers and PMUs has been designed and partially built [2], [9]. The main motivations for this project are the fact that the accurate measurements of power have recently evolved and the use of commercially available instruments, based on digital acquisition, has increased the measurement capabilities in a wider frequency range.

For the calibration of these instruments, flexible systems with suitable generation and measurement capabilities are needed. The operations required for the calibration of such systems, starting from the maintained standards, are more complex than the ones employed in traditional systems for sinusoidal wattmeters, but these operations ensure, then, the possibility to calibrate large sets of instruments. Specifically:

- power frequency and wide-band wattmeters and energy meters for both sinusoidal and distorted waveforms;
- analyzers for the detection and classification of, power quality events;
- phasor measurement units and system for their calibration.

The second project concerns the construction of accurate and gain matched voltage amplifiers for scaling up the output signal of a home-made synthesizer based on a dual high update rate semiconductor DAC [10]. This improved version will be used for the traceability and dynamic characterization of wideband precision sampling systems. For this purpose a new experimental setup is being developed at INRIM and will allow its calibration against a pulse-driven AC Josephson voltage standard

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(JAWS) by using a synchronous detection technique for frequencies beyond the acoustic band.

Although with different characteristics and aimed performances, both projects need resistive dividers. In the first project the main problem is the dissipation, which requires resistors of comparatively high value. This, combined with their not negligible stray capacitances, limit the bandwidth of the dividers. In this case, in order to share the power among the components, the series-parallel solution appears to be the most appropriate one.

In the second project, where the dissipation is more limited and the resistors can be chosen to reduce the influence of the stray parameters to a minimum, the structure can also be different (for example various types of ladder structures). In the next section the series-parallel, which have been thoroughly analyzed, will be explained in detailed as a starting point for the development of methods for its metrological characterization.

III. DESIGN OF SERIES - PARALLEL RESISTIVE DIVIDERS

A. Design criteria

The input voltage of the designed power analyzer is up to 600 V and the main requirement for the dividers of this instrument is the stability of the voltage ratio between the input and the output both as value and phase difference.

The operative frequency range of the instrument as power analyzer is up to the 50^{th} harmonics, where the voltage level of the harmonic components is measured. However, to be used also as a wide-band wattmeter, the accuracy should be acceptable also for higher frequencies. So, the characteristics of the divider should be as far as possible independent of the frequency.

The resistive divider can be provided by variable elements (resistors and/or capacitors) for its adjustment to be adaptable for the connection to the different channels of the digitizer.

B. The model of the series- parallel resistive dividers

The design of the resistive divider is based on a series-parallel structure, where the elements are equal. With this assumption, the resulting divider is theoretically compensated and the behaviour as function of the frequency is flat. This is true for every reasonable circuit used to represent the resistors, because the equivalence of the stray components automatically compensate the structure.

A scheme of the series-parallel resistive divider is shown in Fig. 1.

However, if the stray components are different in each component, or additional stray capacitances, C_S, are added to the circuit, as for example between the resistors and ground, the divider is not exactly compensated. In

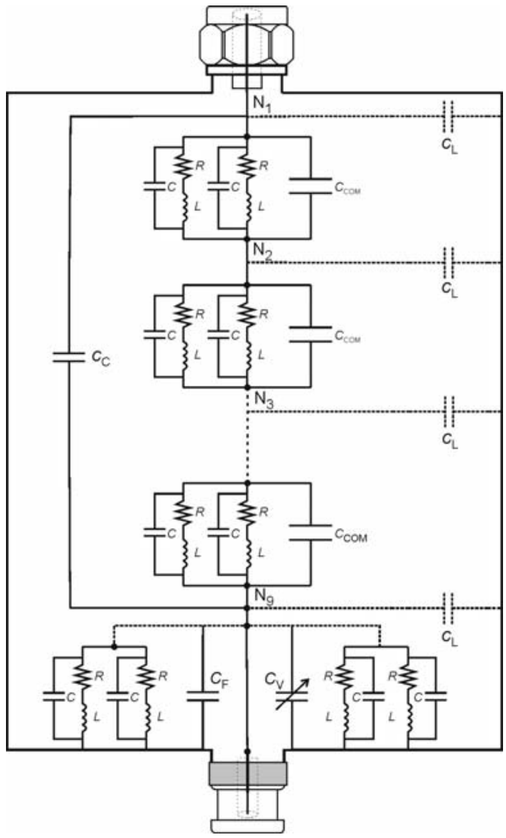

Fig. 1 Schematic of the coaxial resistive divider. For simplicity only a limited number of cells are shown; the high part consists of series connection of n=10 single compensated cells, instead the low part consists of a parallel arrangement of m=10 like high precision resistors.

this case additional capacitors must be added, C_C. In order to compute the values of these capacitors, more elaborate models in Pspice were developed.

C. Implementation of the dividers

In the first prototypes of the dividers built at INRIM [11] the components used were SMD metal foil resistors. For input voltages greater than 100 V the nominal resistance was 10 kΩ with a thermal coefficient at ambient temperature less than 10^{-6}/°C. As their maximum rate power is 600 mW, each resistor can sustain up to about 75 V, even if a reduced voltage (less than one half) is suggested for a better stability of the divider. In one side of the divider the resistors were put in series on printed board. On the basis of the evaluated capacitance between the resistors and ground suitable ceramic capacitors were put in parallel. The resistors in parallel were placed on a circular printed board similar to that used for the construction of the coaxial shunts [12]. The two printed boards were connected together and enclosed in a copper coaxial screen and terminated by two connectors. The number of resistors in series and parallel

Fig. 2 A photograph of the internal part of a resistive divider

depends on the specific ratio to be implemented.

For the fine adjustment of the phase compensation a variable capacitor was connected in parallel to the output. The value of the capacitor was selected to take into account the compensation of digitizer input capacitance and the additional short connection coaxial cable.

One of this prototype (approximate ratio 250 V/5 V) is shown in the photograph of Fig. 2 and it is made of 10 compensated series cells each one composed by two 10 kΩ resistors and one capacitor connected in parallel and 10 resistors arranged in parallel.

IV. ADJUSTMENT

The resistive dividers described in the previous section, are manually adjusted by acting on the variable elements. A variable resistor can be used for the ratio adjustment (in the model described the ratio is evaluated and corrected via software) and a variable capacitor is used for the compensation of the phase difference between the input and the output.

A. Ratio adjustment

The adjustment of the ratio of the resistive divider can be performed with the suitable dc voltages supplied by a calibrator. The voltages at the input and at the output of the resistive dividers are read by a voltmeter. Considering the not negligible output resistance of the divider, the voltmeter selected should have high input impedance. To simulate the impedance of the acquiring instrument, a load with suitable impedance can be connected in parallel to the voltmeter. The two voltages are read and the ratio is computed and used for computing the ratio or, if a variable resistor is added to the divider, the ratio can be adjusted at the nominal ratio.

B. Phase difference adjustment

The adjustment of the phase in a resistive divider can be made by means of a fixed capacitor, C_F, and a variable capacitor, C_V, shown in the circuit of Fig. 1. Another resistive or inductive divider with suitable nominal ratio characterized in phase is required. The phase difference between the resistive divider under test and the reference divider is evaluated by supplying the same voltage to both inputs and comparing their outputs by means of a phase detector.

Alternatively, for a first preliminary adjustment, the resistive divider is supplied to the input by sine-wave generator at an appropriate high frequency (for example 100 kHz – 1 MHz) and an oscilloscope of 1 GHz bandwidth is used to see the phase difference between the input and the output.

V. CALIBRATION

The calibration process, developed for the resistive dividers, at the moment mainly oriented to the series-parallel type, is aimed at their characterization at the best level allowed by the national standard. The calibration can be performed as single devices or as part on a complex instrument (ie. the divider connected to a digitizer) and includes different steps.

A. Ratio in dc or at low frequency

The first step of the calibration can be performed either in dc or in ac at low frequency, for example at 1 kHz, where the accuracy is at the best level. In dc, the resistive divider is supplied by a high stability dc calibrator. If required, the divider can be connected either to the digitizer channel or to equivalent impedance. Two high accuracy voltmeters previously calibrated are connected respectively to the input and the output of the resistive divider. The higher input impedance possible is selected for the voltmeters (in particular it is important for the voltmeter connected to the output) and if necessary a further correction for the impedance partition is considered.

The calibration at low frequency can be performed by means of the INRIM system for the calibration of the inductive dividers, with some specific precautions due to the comparatively higher output impedance of the resistive divider.

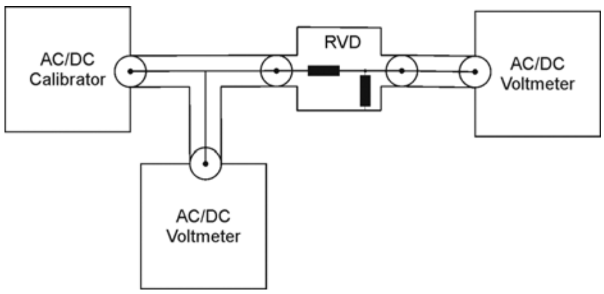

Fig. 3 Schematic for the calibration of ac/dc transfer error of voltage dividers.

B. Frequency response

To evaluate the frequency response of the input-output characteristics of the resistive divider, the system represented schematically in Fig. 3 was employed. A calibrator able to switch from dc to ac supplies the voltage to the resistive divider and the ac/dc difference is measured both at the input and at the output. As at the input the equivalent impedance of the generator is low the measurement can be made by a coaxial thermal convert of the set used as primary ac/dc standard. At the output the equivalent impedance seen by the output not negligible, for this reason a programmable high impedance ac/dc instrument (J. Fluke model 5790A, having both in ac and dc a resistance of 1 MΩ in parallel with 40 pF) was used. For each frequency, the input and output ac/dc transfer differences $\delta_{in}(f)$ and $\delta_{out}(f)$ are defined as:

$$\delta(f) = \left. \frac{U_{ac}(f) - U_{dc}}{U_{dc}} \right|_{Eac=Edc} \tag{1}$$

where $U_{ac}(f)$ is the ac voltage as a frequency function that produce the same output (E_{ac}=E_{dc}) at the ac/dc transfer standard.

The ratio of the resistive divider as a function of the frequency *Ratio*(*f*) can be then derived by the input and the output transfer differences and the dc ratio as:

$$\begin{aligned} Ratio(f) &\cong \frac{U_{dc\_out}}{U_{dc\_in}} \cdot \left(1 + \delta_{out}(f) - \delta_{in}(f)\right) = \\ &= DC\_Ratio \cdot \left(1 + \delta_{out}(f) - \delta_{in}(f)\right) \end{aligned} \tag{2}$$

So, by evaluating the ac/dc transfer differences at the input and the output and using relation (2) the frequency response can be evaluated with a high accuracy.

In the determination of the $\delta_{out}(f)$ the contribution of the resistance is cancelled, while the effect of the capacitance has to be taken into account and the frequency response is evaluated with this capacitance at its output.

C. Phase difference

The calibration of the phase difference between the output and the input of the resistive dividers needs the construction of proper reference dividers, which have such differences as function of the frequency perfectly known. Then, the calibration is performed by supplying the same voltage to inputs of both the resistive dividers and by comparing their outputs by means of a digital phase detector. An accurate digital phase detector was built by a two-input high accuracy and high update rate acquisition board and it was already employed and characterized for the system for the comparison of the phase of high current shunts [13].

The construction of a group of resistive dividers with different voltage ratios that can act as reference for the phase difference has been undertaken, and the traceability for the phase is based on a series of comparisons between these dividers. The procedure consists of some steps, starting from a signal not attenuated by any divider, which may act as a reference for the absolute phase. The second step is the comparison of the phase of the direct signals with that of a resistive divider of a suitable ratio, so that the output signal is in the same range of the phase detector. In this way the two signals can be exchanged and the error contribution of the phase detector is cancelled. Then, by subsequent steps in a sort of step-up procedure, the reference of phase difference is transferred to the reference dividers of decreasing ratio.

VI. SOME EXAMPLES OF CALIBRATION RESULTS

For some of resistive dividers already built the calibration procedure has been already tested [12]. A resistive divider (250V/5V) adjusted in phase has been, calibrated by means of two dc voltmeters and the variation between 100 V and 200 V was found to be within 8 parts in 10^6. By means of the second procedure the ratio as function of the frequency showed a parabolic like variation with a change of about 180 parts in 10^6 at 2 kHz. The determination was made with an accuracy of about 20 parts in 10^6, showing that the calibration can be an additional improvement for a resistive divider used as transducer of a power analyzer.

Other tests were performed on the stability of the phase between two resistive dividers supplied with two different voltages. The differences of the phase at their output were contained for frequencies up to 20 kHz within 20 μrad.

VII. CONCLUSIONS

Resistive dividers are of fundamental importance in the construction of modern instrumentation and some project involving them have been undertaken at INRIM. Their design involves different principles, with the main objective to build accurate ratio with a known behavior as ratio value and phase difference. Unfortunately the stray components in the resistive components and in the printed board are not all exactly known and their modeling does not always comply with the expected results. For this reason, in order to use them in high accuracy metrological systems their calibration is necessary.

Traceability for the ratio value of such dividers derives from dc voltage and ac/dc transfer reference standard, while for the phase there is no need of an external reference but it can be derived by proper measurements performed by means of auxiliary dividers.

The steps for the derivation of the traceability have been considered and the results show that the variations of the ratio and phase as a function of the frequency are generally not completely negligible. Corrections by adjustment or by the software of the instrument using the dividers have to be taken into account.

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