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PRECISION MEASUREMENT OF AC VOLTAGES IN THE MILLIVOLT RANGES

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Abstract – The paper describes the systems, the standards and the procedures developed at IEN for the precise measurement of ac voltages in the millivolt ranges. Two different methods based on resistive dividers and wideband transformers have been developed and are applied for the measurements of respectively the ac-dc transfer difference and the ac voltages down to 1 mV.

Keywords Electrical variables measurement, measurement standards, voltmeters, ac-dc thermal converter.

1. INTRODUCTION

At Istituto Elettrotecnico Nazionale "Galileo Ferraris (IEN) the traceability for the precision measurement of ac voltages in the ranges from 0.5 V to 1000 V and for frequencies from 20 Hz to 1 MHz is derived from a set of multijunction and single junction thermal converters [1] periodically compared by means of an automatic system [2]. In this voltage and frequency range the level of uncertainty (1σ) is between 3 parts in 10^7 (3 V - 1 kHz) and 30 parts in 10^6 (1000 V - 100 kHz). The measurement of ac voltages in the millivolt ranges was previously solved only in the frequency range from 40 Hz to 10 kHz, where calibrated ac voltages suitable to be applied to ac voltmeters under calibration were produced by means of an inductive voltage divider.

In recent years new types of instruments such as multirange ac-dc transfer standards, programmable ac-dc transfer standards and precision multimeters have been widely adopted in metrological and industrial laboratories. These instruments require the calibration at a high level of accuracy, over a wider frequency range. So, in order to calibrate them, new activities for developing systems operating at low voltages have been undertaken.

Different methods based on resistive dividers, micropotentiometers and inductive dividers have been considered for the construction of the traceability, its maintenance and the calibration of instruments.

Two of these methods are reported in this paper. They are based respectively on resistive dividers to calibrate the ac-dc transfer standards and on wideband transformers for the calibration of the ac voltmeters in the millivolt ranges and for frequencies from 1 kHz to 1 MHz.

2. THE SYSTEM FOR THE MEASURMENT OF THE AC-DC TRANSFER DIFFERENCE

2.1. The generation of the low voltages

The first system developed is designed for extending the traceability of the ac-dc transfer difference in the millivolt ranges by means of resistive dividers. This system has been set up by combining some new additional standards and devices to the previous system for the comparison of thermal converters [2]. These standards and devices are used to produce at the input of the ac-dc transfer standard under test a sequence of low-voltages in ac and dc. In particular, these standards are:

- a set of single junction thermal converters suitable to be used in the range from 0.1 V to 1 V;
- a set of 0.1 and 0.01 ratio resistive dividers [3];
- a precision battery operated multirange ac-dc transfer standard.

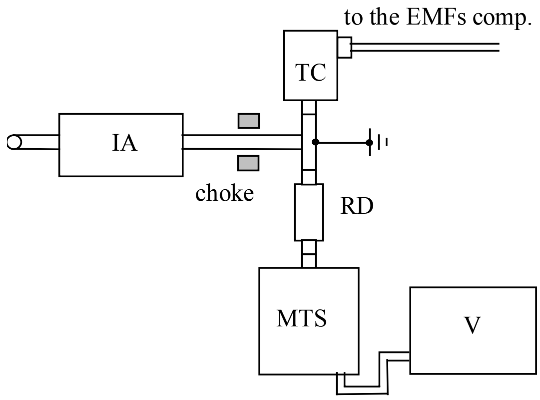

Fig. 1 Combination of additional devices and standards for the calibration of a multirange ac-dc transfer standard (MTS) read by a voltmeter (V). The system for the generation of low calibrated voltages consists of an instrumentation amplifier (IA), a choke, a thermal converter (TC) and a calibrated resistive divider (RD).

The additional components: a wideband instrumentation amplifier, a high frequency choke, and a T connector, beside to the thermal converter are arranged in the proper configuration shown in Fig. 1 and employed as a system for the generation of low calibrated voltages. The thermal converter is used as a reference of ac-dc difference and is connected to one side of the T. The other side of the T is connected to the multirange ac-dc transfer standard to be calibrated, directly or through a calibrated resistive divider.

The instrumentation amplifier and the choke separate the system that supplies the ac and dc voltages from the comparison system, so reducing the interference and the noise originated from the ground connections, which are an important source of unwanted signals and a possible source of errors in the measurements.

2.2. Automatic system for the comparison of thermal converters

The input of the system for the generation of low calibrated voltages is connected to the system for the comparison of thermal converters [2]. This system consists of an ac and a dc calibrator that supply the voltages to a voltage node where the output and the sense terminals of both calibrators, selected by a switch, are connected.

The switch, driven by a IEEE-488 interface, provides a regular sequence (ac, dc+, ac, dc-, ac) of voltages at the node. Each switching operation consists of three steps:

- switch of the senses in the internal position;
- switch of the outputs from ac and dc or vice-versa;
- re-connection of the senses to the voltage node.

The total period of time for switching operation is about 20 ms.

The detection section of the system is employed for acquiring the outputs thermal converters. This section includes an electromotive forces (EMFs) comparator and the connection to the IEEE-488 bus for data input from voltmeters or other programmable instruments. The EMFs comparator is mainly designed for low electromotive forces (a few millivolts in dc) and consists of two thermally protected resistors, where a current is injected by a battery controlled by two resistance boxes. The resistors are connected together to one end and act as the outputs of two Lindek potentiometers, which can be adjusted against the EMFs of the thermal converters under comparison. The difference between the voltages on the resistances and EMFs at the outputs of the converters are read by low-noise amplifiers and acquired by digital voltmeters operating under the IEEE-488 bus control.

In the EMFs comparator the low resistances of the two resistors (1 Ω or 10 Ω), and the low noise of the nanovolt amplifiers allow us to acquire the variations of the EMFs with sensitivity under the nanovolt. In this way, even with the electromotive forces of the single junction thermal converters, it is possible to operate at the resolution level better than 1 part in 10^7.

2.3. The calibration of the system

The calibration for all the ranges between 1 mV and 1 V consists of three main steps:

- the calibration of thermal converters down to 100 mV;
- the calibration of 0.1 and 0.01 resistive dividers;
- the calibration of a multirange transfer standard in the millivolt ranges.

The first step is performed by comparing the thermal converters starting from 1 V, where the specific thermal converter is calibrated directly by means of the national reference standard. Then, the ac-dc transfer difference of this converter is used to calibrate, by means of a step-down procedure, the thermal converters of 0.5 V and 0.25 V nominal values. The T-connector at the output of the system for the generation of low calibrated voltages is connected to the input of the two thermal converters under comparison in parallel, while their outputs are connected to the EMFs comparator. The independence of the ac-dc transfer differences of the applied voltage is assumed and the possible variations are taken into account in the uncertainty budget.

In the second step, the multirange transfer standard is calibrated directly in comparison with the thermal converter calibrated in the previous step at the voltage of 100 mV. Then, it is possible to calibrate the resistive dividers of 0.1 nominal ratio by applying at the T the 1 V thermal converter and connecting the 0.1 nominal ratio resistive divider and the multirange ac-dc transfer standard in cascade to the other side of the T. So, by comparing the two results at 100 mV, the ac-dc transfer difference of the 0.1 nominal ratio resistive divider can be calibrated for all the frequency range up to 1 MHz.

An equivalent procedure is employed for the calibration of the ac-dc transfer difference of the 0.01 nominal ratio resistive dividers. The 10 mV point of the multirange ac-dc transfer standard is first calibrated by the 0.1 nominal ratio resistive divider and by applying 100 mV at the T-connector and comparing a thermal converter with the 0.1 nominal ratio resistive divider in cascade with the multirange ac-dc transfer standard. Then, the voltage of 1 V is applied to the T connector. One side of the T is connected to the 1 V thermal converter and to other side to the input the 0.01 ratio resistive dividers and the multirange ac-dc transfer standard. Also in this case the key hypothesis for the calibration is that the ac-dc transfer difference of the resistive dividers is independent of the applied voltage.

Having calibrated the thermal converters in the range from 100 mV to 1 V and the resistive dividers of 0.1 and 0.01 nominal value, the multirange ac-dc transfer standard can be calibrated for all the voltages in all ranges from 1 mV to 1 V by a combination of the suitable thermal converter and a proper calibrated resistive divider.

As the ac-dc difference of the resistive dividers depends also on input impedance of the instrument to which they are connected, a particular method ha also been developed for correcting their calibration by taking into account the load variations in the different steps of the procedure.

2.4. Tests and results

Preliminary tests have been performed to verify some aspects of the comparisons, such as the consistency and repeatability of the results, the influence of the connections and the variations of the ac-dc transfer differences with the applied voltage and load impedance. In a battery operated multirange ac-dc transfer standard at 10 mV the typical standard deviations of the results are less than 20 parts in 10^6, using a 0.1 ratio resistive divider and a 100 mV thermal converter (0.25 V nominal value), and less than 5 parts in 10^6, using a 0.01 ratio resistive divider and a 1 V thermal converter.

The effect of the amplifier and the choke was also tested with one or two chokes in series and with different ground connections.

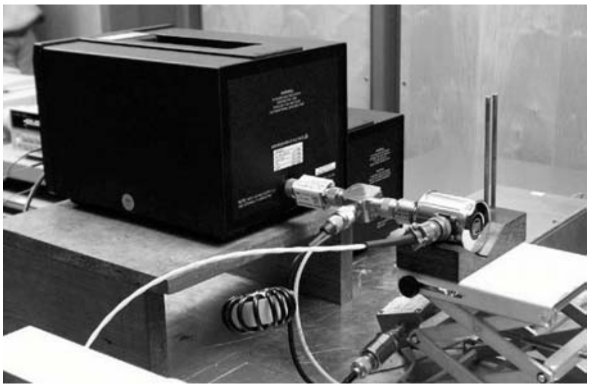

Fig. 2 System for the comparison of thermal converter and the multirange ac-dc transfer standard in the millivolt range and a resistive divider connected in cascade.

The system described is now used at IEN for the calibration of multirange ac-dc transfer standards and programmable transfer standards with the level of uncertainty required by these instruments.

3. WIDEBAND TRANSFORMERS FOR STEPPING DOWN THE AC VOLTAGE

Transformers can be used for the generation of calibrated ac voltages in different ways. In particular, at IEN two methods have been experimented. The first method employs a simple one-stage wideband transformer, which is calibrated at a specific frequency in comparison with an inductive divider. The second method is based on a double-stage transformer that, for the accuracy level of its input-output ratio at intermediate frequencies, does not need such a calibration.

In both methods the reference at intermediate frequency is strictly necessary only when the calibration of the ac voltmeter (for example between 0.3 V and 0.3 V) is performed as a transfer standard. Nevertheless, the second method, even if slightly more complex, has been found more convenient and adopted for the measurements.

3.1. Prototypes of wideband transformers

A first prototype was built as a simple 0.1 ratio transformer by winding the appropriate number of turns on an amorphous magnetic core. This prototype has been tested for distortion in the range from 10 mV to 300 mV and the parameters of the transformer have been measured with an input voltage of 20 mV, 100 mV and 1 V by a high frequency automatic bridge. The evaluation of the relative error of the ratio, computed from these parameters, shows that for all frequencies the difference between the ratio with two different voltages is lower than 50 parts in 10^6 and in particular is lower than 3 parts in 10^6 in the frequency range from 20 kHz to 1 MHz.

The double stage transformer has also been investigated. In this transformer a core is employed to generate the main part of the magnetic flux necessary to support the electromotive force. The additional magnetic flux is supplied to the other core by a second stage with the same number of turns winded around both cores.

Also in this case the parameters have been measured with the primary and secondary windings in a proper configuration (open or in a short circuit) and the input-output characteristic has been evaluated by means of the circuital model shown in Fig. 3.

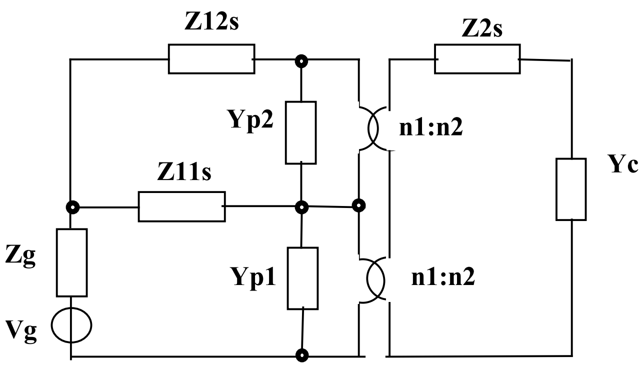

Fig.3 Circuital model of a double stage transformer

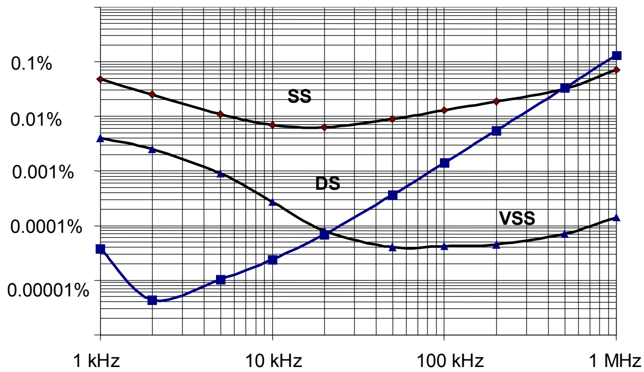

Fig. 4 Relative error of the ratio for the single stage (SS) and the double stage transformer (DS) and variation of the error ratio with the applied voltage in the single stage transformer (VSS). The determination of the ratio error has been performed under the following conditions: Vg=100 mV, Zg=0 n1:n2=30:3, Yc=40 pF in parallel with 1 MΩ.

By means of the model the input-output ratio as a function of the frequency can be evaluated for both the single stage and the double stage transformer. The results are shown in Fig. 4, where also the variations of the error with the applied voltage (from 20 mV to 1 V) is drawn for the single stage transformer. In the double stage transformer the variations of the ratio for frequencies lower than 10 kHz are of course lower than the value of the ratio error, while for higher frequencies they maintain almost the same level as in the single-stage transformer.

From the graphs shown in Fig. 4 the relative error computed from the parameters shows that for frequencies lower than 30 kHz the ratio error is less than 3 parts in 10^6. In all range between 1 kHz and 1 MHz the variations of the ratio error at different voltages in the double stage transformer are also less than 3 parts in 10^6.

Taking into account the results of the experimental tests and the evaluation of the input-output characteristic by means of the parameters, the design of the prototype of the wideband transformer has eventually evolved into a composite transformer with two sections that can be connected in cascade and configured as a double-stage transformer for either the 0.1 or the 0.01 nominal ratio.

3.2. Tests on the wideband transformer

Some experimental tests have been performed on the prototype. The value of the ratio has been measured at the frequency of 1 kHz by means of the IEN system for inductive voltage dividers [3]. At this frequency the error relative to the output in the 0.1 ratio is 15 parts in 10^6 and the error in the 0.01 ratio is less that 10 part in 10^6. Other tests, performed by means of two ac voltmeters calibrated as ac-dc transfer standards by resistive dividers have shown that the resulting error of the transformer at 1 MHz is less than 0.5%, as expected by estimation from the parameters. The variation of the transformer ratio with the applied voltage has been verified to be zero within the uncertainty of the calibration of the voltmeters.

The variation of the ratio with a variation of the load is instead not negligible. As shown in Fig. 5, the sensitivity to the capacitive load variation is particularly high (~20 ppm/pF at 1 MHz) and it is nearly proportional to value of the capacitance variation and to the square of the frequency in the range form 300 kHz to 1 MHz.

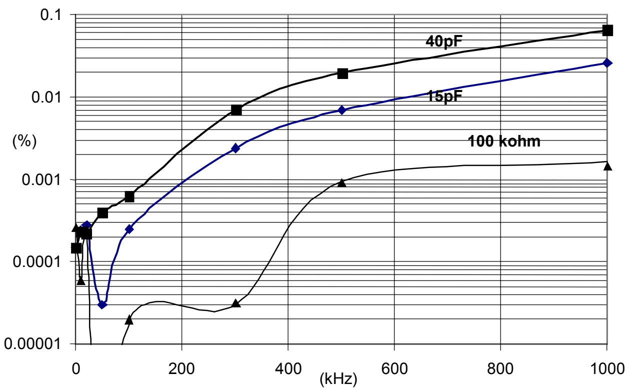

Fig. 5 Relative variation of wideband transformer ratio as an effect of the load variation at its output. The value of the load variation, 40 pF, 15 pF and 100 kΩ respectively, is shown as label of the graphs.

3.3. Calibration of ac voltmeters by means of double stage transformer

For the calibration of the single-stage transformer an inductive divider is preliminarily used at intermediate frequencies to transfer the calibration for ac voltages from the range of a few volts measured by the calibrated voltmeter, to the second ac voltmeter operating in millivolt range. At 1 kHz the additional relative uncertainty introduced by the ratio of a two stage inductive divider is generally less of 1 part in 10^6 for 0.1 ratio and less than 10 parts in 10^6 for the 0.01 ratio. The double-stage transformer is used directly, without calibration at intermediate frequency and the error ratio is taken into account in the uncertainty budget.

The procedure is based on the stability of the transformer ratio as a function of the applied voltage. The ratio of the transformer is calibrated in the whole frequency range by means of the two voltmeters in the configuration shown in Fig. 6 and then is employed to extend the traceability down to the other ranges.

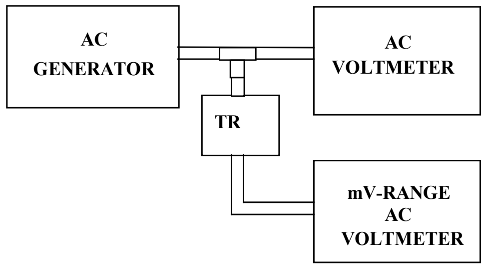

Fig. 6 Calibration of an ac voltmeter in the millivolt range by comparison with another ac voltmeter and a wideband transformer.

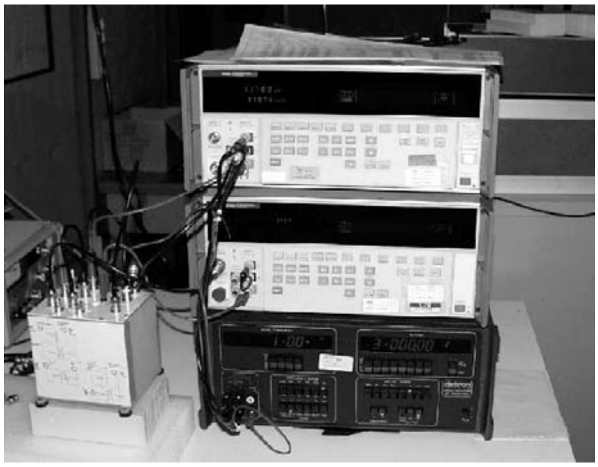

Fig. 7 Calibration of a precision ac voltmeter in the millivolt range in comparison with another ac voltmeter and the wideband transformer.

4. CONCLUSIONS

The extension of the traceability of ac-dc transfer measurements to low voltages by means of the resistive dividers in the frequency range from 20 Hz to 1 MHz has been demonstrated. Furthermore, the analysis and the experimental results on the prototype of single and double stage wideband transformers have shown that these methods are suitable for a simple calibration of the ac voltmeters in the range from 10 mV to 300 mV for frequencies from 1 kHz to 1 MHz.

The uncertainty of both methods depends on the specific value of the voltage and the frequency of the measurement. Although further investigations are necessary to reduce the load sensitivity in the wideband double stage transformer at high frequency, for both methods the uncertainty is less than

50 parts in 10^6 for a voltage down 10 mV and a frequency up to 1 MHz.

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