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Bridging a Gap between Low and High Frequency Measurements

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***Abstract*-** INRiM's primary AC-voltage standard is realized by means of a set of AC-DC Thermal Voltage Converters from DC range up to 1 MHz. Above this frequency, an AC-voltage standard has not been normally implemented because of low technical interest. Indeed, in that range, electromagnetic power, a quantity that is always well definable and measurable also at higher frequencies, becomes more interesting than the AC-voltage. Power standard is realized by means of microcalorimetric technique that, however, lacks in precision under 10 MHz. The result is a metrological gap from 1 MHz to 10 MHz, in which any electrical standard exists, at least at INRiM. To fill this gap a new measurement setup is now under development and characterization, which will allow performing AC-DC Transfer Difference measurement up to 100 MHz and realizing a low frequency power standard. In this paper a description of this new setup will be given together with a set of measurements.

Keywords: AC-voltage, AC-DC voltage thermal converter, power, standard, calibration.

I. Introduction

The alternate current (AC) voltage standard is given at low frequency (<1 MHz) in terms of a quantity called AC-DC *Transfer Difference* defined as follows:

$$\delta = \frac{V_{\mathrm{RF}} - V_{\mathrm{DC}}}{V_{\mathrm{DC}}}, \tag{1}$$

where V_{RF} is the radio frequency (RF) voltage that produces the same output of the direct current (DC) voltage V_{DC} when both are applied to the reference plane of the input connector of a thermal voltage converter (TVC). This standard is realized from DC up to 1 MHz only, at least by INRiM. It is very important however to extend the AC-voltage measurements above this frequency value, for satisfying technical demands of INRiM high frequency laboratory, but also for the commercial aspects. Indeed between 1 MHz and 10 MHz there is a metrological gap that has not been filled until now. The microcalorimetric standard [1, 2] works well from 10 MHz up to 26.5 GHz (extendible to 40 GHz [3] and beyond) but it lacks in precision below 10 MHz, due to the fact that in this range it is not possible to have a good signal detection for noise excess. A new measurement setup is however under development for extending AC-DC Transfer Difference above 1 MHz up to 100 MHz. In this manner we will have also the possibility of realizing a power standard through AC-voltage measurements, particularly between 1-10 MHz, where the microcalorimeter is not usable.
The measurements will be performed on the same thermal loads used by the microcalorimeter. Because the devices, i.e. thermoelectric power sensors, can work also in DC, they can be calibrated in terms of transfer difference too by comparison against commercial Single Junction Thermal Voltage Converters which are used to realize INRiM AC-voltage standard up to 1 MHz.
Very soon, a specific Calorimetric Thermal Voltage Converter (CTVC), will be used, that was designed and built by INRiM [4]. The project is to replicate this first prototype in order to have a set of CTVCs more robust than the commercial ones and that can extend the AC-voltage standard up to 1 GHz.

II. The Measurement Setup.

Figure 1 shows the details of the new measurement setup. The DC Source, which is a calibrator, and the Synthesized Generator, that works as the RF Source instead of the classical AC calibrator, are both connected to a RF-switch. This one supply a symmetrical Tee Junction (designed at INRiM [5]) in its electrical centre, while the Device Under Test (DUT) and the Reference Standard are connected to the two Tee's branches. The output signals of the two devices are measured with two nanovoltmeters. All the instruments are controlled through a personal computer connected with a GPIB – IEEE 488.2 bus.

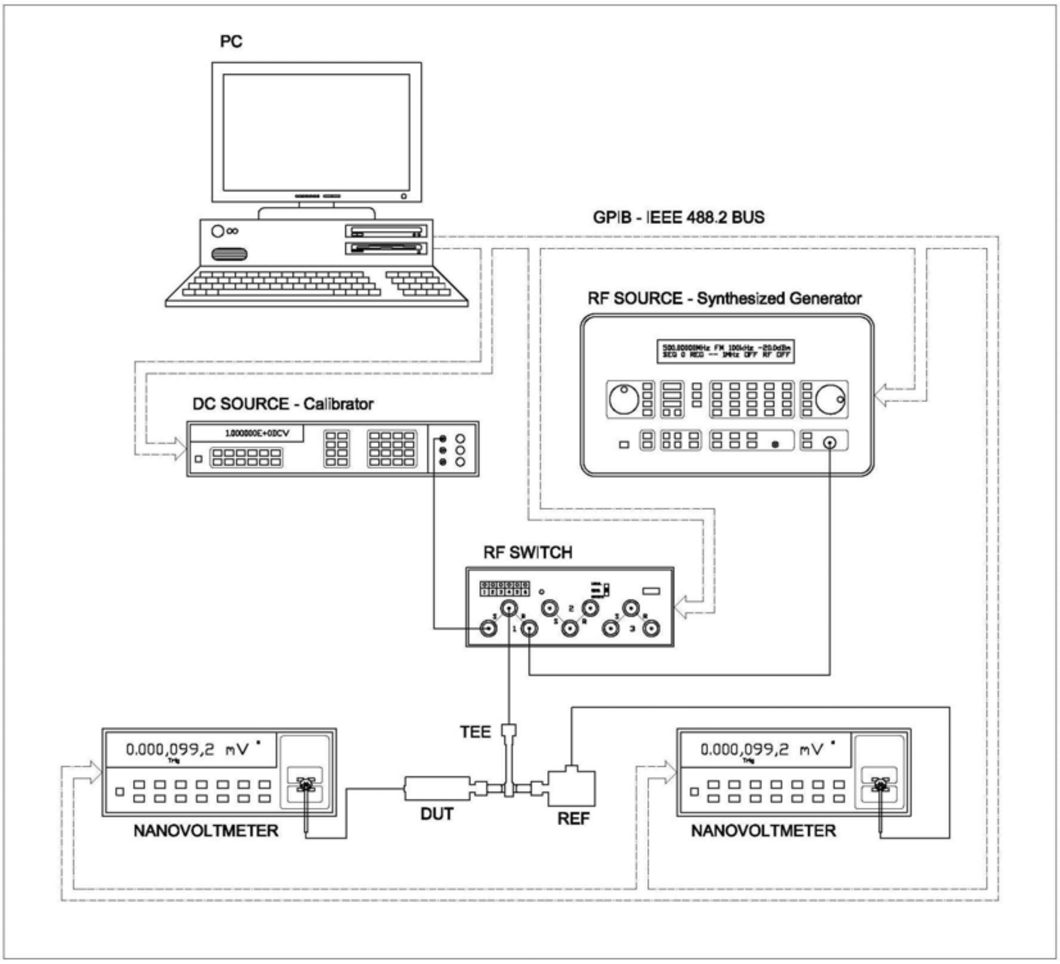

Figure 1. Measurement Setup

Theoretically, with this setup it should be possible to perform AC-DC Transfer Measurement from 9 kHz to 2 GHz but the real interest is to limit the range at 1 GHz at maximum, both because the microcalorimetric technique gives better results at higher frequencies and the AC-voltage measurements have less significance.

At the moment measurements have been limited at 100 MHz in order to control the whole system better. Since the new Thermal Voltage Converter is still under characterization, all the measurements have been performed using two different device types: a commercial Single Junction Thermal Voltage Converter and another Single Junction Thermal Voltage Converter specifically designed and calibrated by the NMI VSL. The first TVC does not need a specific calibration because it is used in differential configuration, while the second TVC has been used as reference standard, having a Calibration Certificate from 1 MHz up to 100 MHz coming from an independent source.

III. AC-DC Transfer Difference Measurement Rationale

The thermocouple sensors used at INRiM in the microcalorimeter are commercial power sensors modified by removing all active internal electronic, so that the signal of the thermopile can be directly measured by means of a nanovoltmeter. These devices become power transfer standards once they are calibrated in terms of effective efficiency, whose most general definition can be given by the following expression:

$$\eta_e = \frac{P_M}{P_M + P_X}, \tag{2}$$

where P_M is the measured power, i.e. the power converted into the sensor dc-output, and P_X is the power loss in the sensor mount at the same frequency. An alternative way to characterize a power transfer standard is considering the relative difference Δ in the power that is required to give the same response on alternate and direct current regime, that is:

$$\Delta = \frac{P_{\mathrm{HF}} - P_{\mathrm{DC}}}{P_{\mathrm{DC}}}, \tag{3}$$

where P_{HF} is the high frequency measured power, and P_{DC} is the reference DC-power producing the same instrument output, this being a DC-voltage output U for us.
On other side, an equivalent definition of the effective efficiency (2) can be given in terms of the ratio between the DC-power and the HF-power that entering the device produce the same sensor output [6, 7], that is:

$$\eta_{\mathrm{e}} = \left.\frac{P_{\mathrm{DC}}}{P_{\mathrm{HF}}}\right|_{U=const} \tag{4}$$

From (3) and (4) we can express η_{e} in terms of power relative difference Δ as follows:

$$\eta_{\mathrm{e}} = \frac{1}{1+\Delta} \tag{5}$$

Power transfer difference Δ is not directly measurable, but since the used thermoelectric power sensors have the same structure of the TVCs employed for voltage standard comparison in coaxial lines [8], they can be calibrated in terms of *voltage transfer difference* δ, defined as in (1). The effective efficiency can thus be derived from equation (1), at a first order approximation, as follows:

$$\eta_e \cong \frac{R_{\mathrm{HF}}}{R_{\mathrm{DC}}} \frac{1}{(1+2\delta)}, \tag{6}$$

where R_{HF} and R_{DC} are the HF and DC resistance respectively at the input reference plane of the thermoelectric power sensors.
Experimental results hereby presented have been obtained in a range of frequencies from 1 kHz to 1 MHz and concern a commercial Type N power sensor already used in the microcalorimeter as transfer standard. The sensor was modified, as before mentioned, so that the signal of the thermopile can be directly measured by means of a nanovoltmeter. The measurements shown in figure 2 refer to the actual AC-DC Transfer Difference of the sensor calibrated against the INRiM AC-voltage Primary Standard.
The transfer difference so obtained has been transformed in effective efficiency, by means of formula (6). In this manner we have implicitly realized a power standard at the frequency of 1 MHz and below. At the moment this result is impossible to obtain by means of the microcalorimetric technique, with comparable accuracy at least.
The power sensor, which equation (6) applies to, exhibits an effective efficiency approaching the unity only in DC, because of its losses that increase proportionally with the frequency. Since the effective efficiency is defined as in (4), the HF power level P_{HF} must exceed the power at lower frequency P_{LF} indeed to obtain the same sensor output.
With this hypothesis, the expected AC-DC Transfer Difference δ appearing in (6) and determined by (1) should be always > 0, because an higher V_{RF} is required, indeed, to obtain the same output produced by V_{DC}. Consequently the quantity $(1+2\delta)$ is > 1 and can give a result compatible with (4). These details are not trivial because some of the TVCs used for RF-voltage measurements can exhibit a negative transfer difference, but this should be not our case.
In figure 3 a first series of results is shown which have been obtain with equation (6). At low frequencies values of η are slightly greater than one, but still consistent with the hypothesis. In these case the values greater than 1 are the consequence of measurement uncertainties and an imperfect error correction. The value of the HF-resistance R_{HF} needs to be amended from a bias error produce by the measurement system and furthermore the effects due to the residual mismatches have not yet been included, indeed.

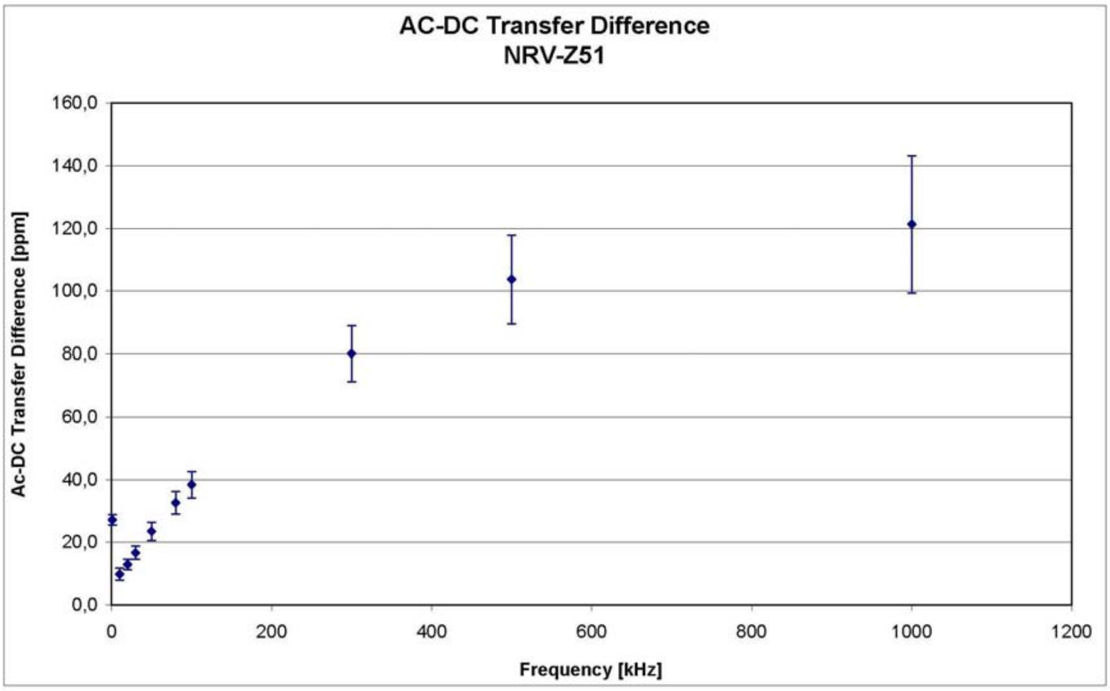

Figure 2. AC-DC Transfer Difference of the Modified Sensor

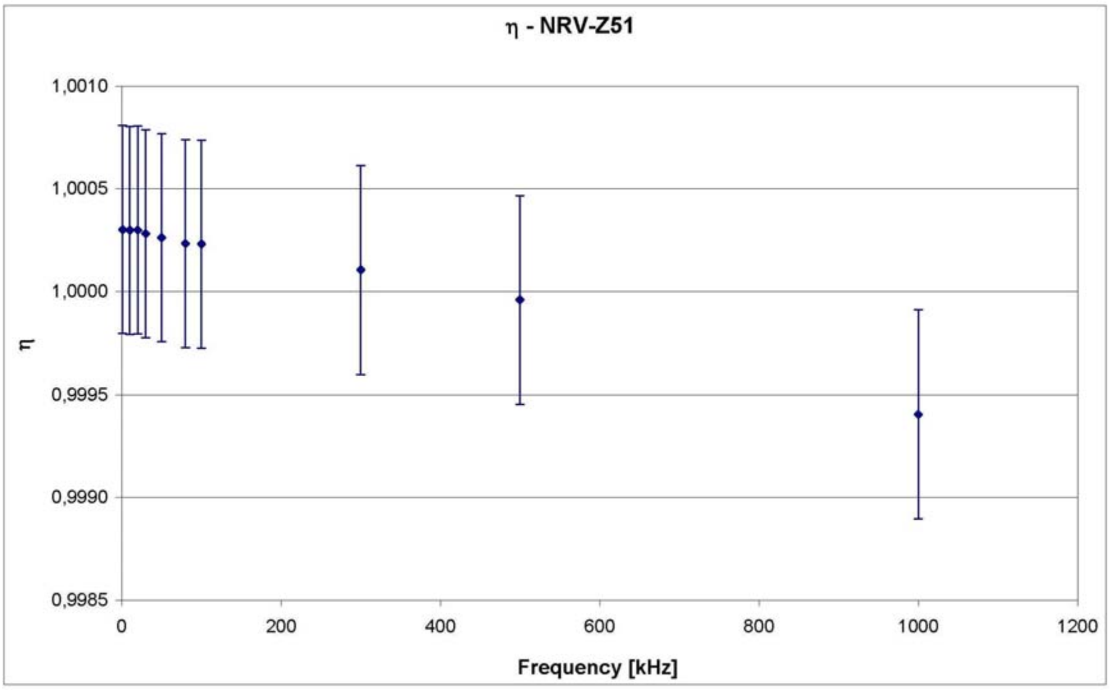

Figure 3. η of the Modified Sensor

In figure 4 a new series of measurements is shown. These measurements cover a range of frequencies from 1 MHz to 100 MHz. They have been performed using, as reference standard, the Single Junction Thermal Voltage Converter specifically designed and calibrated by NMI VSL cited above, and the HF Resistance of the Sensor under test has been measured through a Vector Network Analyzer instead of an Impedance Meter. The η-value at 100 MHz appears to be lower than the expected one: considering that the data shown have not yet been corrected, this could be due to the mismatch between the devices under tests. This behaviour is still under investigation.

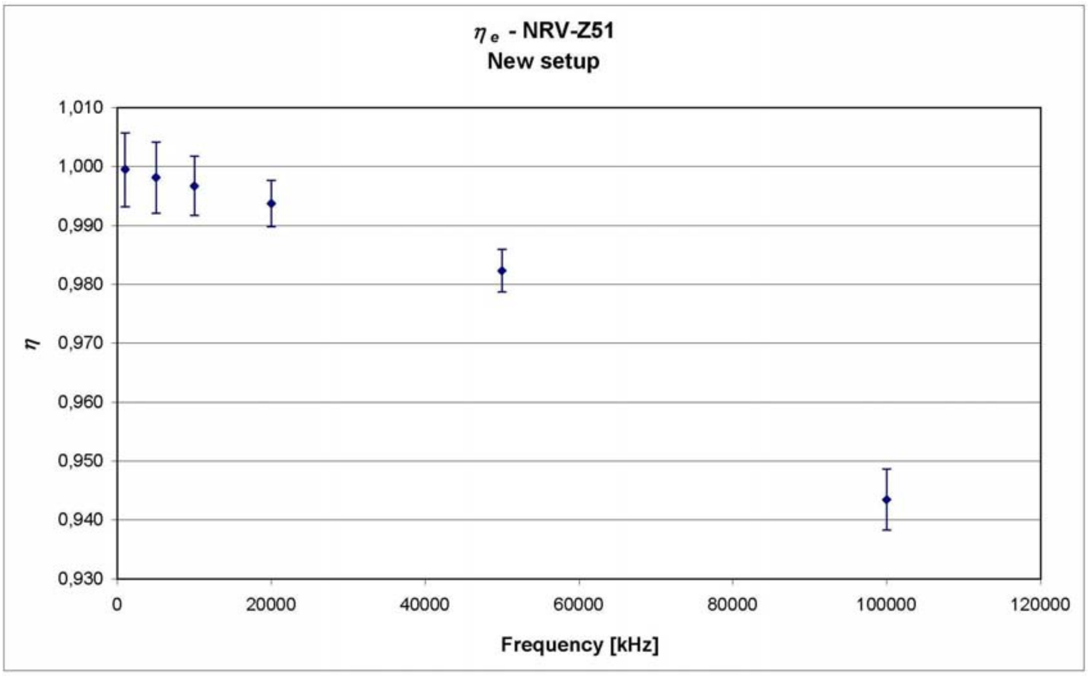

Figure 4. η of the Modified Sensor measured for comparison against the NMI VSL's TVC

IV. Conclusions

In this paper a setup for AC-DC Transfer Difference measurements from DC to 1 GHz is presented. Preliminary measurements of transfer difference have been performed up to 100 MHz on a modified thermoelectric power sensor. Afterward the transfer difference has been transformed in effective efficiency so to realize de facto a power standard traceable to the primary AC-voltage standard. The main aim of this work is to eliminate the frequency gap 1-10 MHz in the INRiM capabilities. Moreover a specific set of CTVCs should also extend the INRiM AC-voltage standard beyond 1 MHz and provide an alternative to the microcalorimetric technique possibly up to 1 GHz.

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