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RF-POWER STANDARD FROM AC-DC THERMAL CONVERTER

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Abstract: Below the frequency of 10 MHz, the calibration fails of electric power sensors made by means of microcalorimeters, mainly because of a reduced sensitivity of the measurement system. This produces a metrological gap in the power standard between the low frequency and radio frequency range. However, as TEM transmission line admits pseudo potential functions, power sensor calibration can be done on coaxial line also in term of RF voltage from DC up to 100 MHz at least. The paper describes how INRIM implements this calibration technique together with the obtained accuracy.

Key words: Power, RF-Voltage, Standard, Calibration**.**

1. INTRODUCTION

Typically the broadband power standard is realized with coaxial microcalorimers [1], [2], [3] from 10 MHz up to 40 GHz, exceptionally to 50 GHz, whereas beyond these frequencies, the band limited waveguide version is mandatory, [4], [5], [6].

Indeed, at millimetre wavelengths, the intrinsic losses of the coaxial microcalorimeter become so high that make unacceptable the final accuracy of the power standard even if correction for losses is made. Both resistance and thermoelectric sensors can be used with the microcalorimeter, because both the types allow tracing the measurement of the radio frequency (RF) power to DC, which is a SI quantity [1], [2]. However microcalorimeter technique fails to be useful below 10 MHz, independently of the sensor type under calibration.

Thermistors are not usable at low frequency (LF) because of an internal decoupling capacitance between RF line and dc-circuitry that reduce its insulating action between the HF and dc sections [2]. Conversely, a specific type of thermoelectric sensor, i.e. indirect heating thermocouple, has not such a limitation below 10 MHz.

However, measurement is in trouble of the sensor mount *effective efficiency* η_e, i.e. the parameter that defines the power standard [7], because the measurement system lacks of sensitivity. Losses both of the microcalorimeter and of the sensor mount are so small that are undetectable and in turn this reduces accuracy of measurand η_e.

In any case, η_e is measured directly only at RF and beyond. Below 10 MHz, η_e and related uncertainty are mainly obtained by means of a linear extrapolation and concern only the thermoelectric detectors [8], [11]. At RF, there is an alternative to classic microcalorimeter technique based on pseudo-potential functions that exist for the transmission lines, like the coaxial ones, which work on TEM modes, [8].

These functions allow describing electromagnetic energy propagation in term of the so-called RF-voltage.

The root mean squared (RMS) of RF-voltage can be measured by means of a RF-DC (or AC-DC) thermal voltage converter (TVC), a device that is considered a RF (or AC) voltage standard, under some assumption and limitation [9] [10]. Such a standard is characterized by a parameter defined as *rf-dc voltage transfer difference* δ. This can be used to calibrate power sensors that behave as TVCs, as the case is of indirect heated thermocouples. In the paper we describe the calibration of the power sensors against TVCs assumed as RF-voltage standard. Experimental results will be given in the frequency band from 1 kHz to 100 MHz, though we are mainly interested to cover the LF range from DC to 10 MHz in which the INRIM broadband microcalorimeter is not useable.

2. TRANSFER DIFFERENCE δ AND EFFECTIVE EFFICIENCY η_e

If equal RF and DC powers are supplied alternately to the input of an ideal TVC, the device output is the same for both powers. For real TVCs, instead, non-joule heating and frequency response of the circuit components produce different outputs for same powers.

This behaviour can be accounted in term of effective efficiency that is appropriately defined by the following formula:

$$\eta_e = \left.\frac{P_{DC}}{P_{RF}}\right|_{E_U = \text{const}}, \qquad (1)$$

where P_{DC} and P_{RF} are the power levels supplied respectively to the device by the DC and by a RF signal that give the same device output E_U.

Thermal voltage converters can be characterized also in terms of transfer difference δ defined as in the following:

$$\delta_{\mathrm{RF-DC}} = \left.\frac{V_{\mathrm{RF}} - V_{\mathrm{DC}}}{V_{\mathrm{DC}}}\right|_{E_{\mathrm{RF}} = E_{\mathrm{DC}}} \quad (2)$$

where V_{RF} and V_{DC} are respectively the RMS voltage of a sinusoidal waveform and the DC voltage that produces the same TVC output (E_{RF}=E_{DC}) [12]. Transfer difference is a terminology mainly used in the low frequency field, where it is not yet necessary to question the validity concept of AC voltage that conversely becomes weaker when signal enters in the RF field. Indeed, literature reports (2) by using very often the acronym AC instead RF. Conversely the term effective efficiency is used mainly in the high frequency field in connection with the power sensor calibration with microcalorimeter technique.

The two quantities (1) and (2) are anyway related through:

$$\eta_{\mathrm{e}} = \frac{R_{\mathrm{RF}}}{R_{\mathrm{DC}}} \frac{1}{\left(1+\delta\right)^2} \quad (3)$$

where R_{RF} and R_{DC} are the RF and DC resistance respectively, measured at the input reference plane of the device. Formula (3) is obtained by applying the Omh's Low $P = V^2/R$ in (1) and rearranging (2) as:

$$\delta + 1 = \frac{V_{\mathrm{RF}}}{V_{\mathrm{DC}}}. \quad (4)$$

Transfer difference is usually a very small quantity compared to unit, therefore (3) can be approximated to:

$$\eta_{\mathrm{e}} \cong \frac{R_{\mathrm{RF}}}{R_{\mathrm{DC}}} \frac{1}{\left(1+2\delta\right)}. \quad (5)$$

Because the devices used to realize both the RF-voltage standard and the RF-power standard have the same structure of a TVC, that is, they are detector of thermal type, then voltage standard and power standard can be calibrated one against other, either in term of δ or in term of η_{e}, according to the experimental convenience. The authors use this possibility to implement the power standard below the critical frequency of 10 MHz, at least.

3. EXPERIMENTAL SETUP

Figure 1 shows the measurement set-up scheme used by the authors to calibrate power sensors in term of transfer difference δ [13]. The circuit is the typical one used in literature for determination of the AC-DC transfer difference of TVCs from the audio frequencies up to the RF field [14]. The kernel of the set up may be identified with the *symmetric* coaxial T-junction.

Indeed, the RF or DC voltage, maintained by the generators in its centre, is conventionally considered as the reference voltage for the system and for all the TVCs connected to it.

The RF and DC signals are supplied to the central port of the junction trough an electromechanical coaxial switch that assures a rapid commutation of the generators without create spurious signal due to the contact bounce. The RF and DC signal are provided by a synthesized generator and by a high performance calibrator respectively. At the lateral ports of the junction are connected the TVC that works as RF voltage standard and the unknown TVC, i.e. the power sensor whose transfer difference or equivalently effective efficiency must be determined.

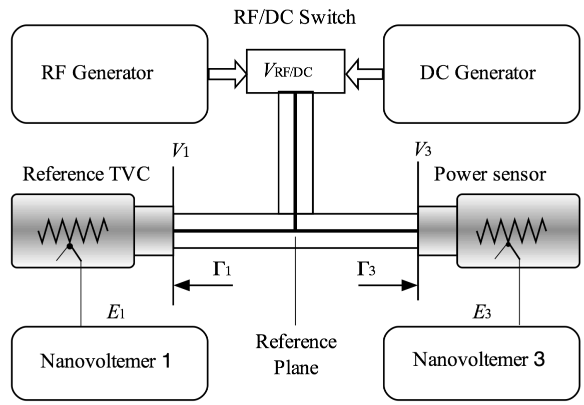

Fig. 1. Measurement set-up for calibration of RF-DC thermal converter and RF power sensors in terms of RF-voltage standard.

The determination of the transfer difference δ is made of the power sensor, by comparing it against the reference TVC with the procedure used to realize the RF-voltage standard [8], [9]. Such procedure differs a little from that typically used to transfer the AC voltage standard in the audio frequency field. Indeed, below 1 MHz the measurand is typically obtained from the TVC outputs measured by the nanovoltmeters, whereas, in our case, the real metering instrument is the DC calibrator, being the two nanovoltmeters used in the role of null detectors only. This operating mode is related to the necessity of knowing directly the RF voltages at the input of the TVCs, voltages that must be corrected for the mismatch of the same TVCs and for their different electrical length, anyway.

In line of principle the measurement system of Fig. 1 is not sensitive to the mismatches of devices, because both TVCs should see the same reference voltage that the generator maintains in the centre of the T-junction. Unfortunately this is true only if the electrical length of the devices is negligible or the two loads have the same impedance. It being not our case, the correction for the mismatches is therefore mandatory to avoid a significant measurement error.

The whole measurement procedure includes the determination of the S parameters of T-junction, of reference TVC and of device under test (DUT). These parameters are necessary, indeed, for correcting the RF voltage measurements for the mismatch effects that begin to be significant beyond 1 MHz.

4. MEASUREMENT PROCEDURE

Measurement procedure must be presented in detail for better understanding results and reasons of some data corrections. The typical sequence of the operations is the following:

I-step: the system is energized at convenient RF power level by means of a RF synthesizer. For us, it is the power that allows establishing voltage of about 1 V RMS in the junction node.

II-step: the outputs E_{1RF} and E_{3RF} are measured and registered both of the reference TVC and of the unknown one by means of the nanovoltmeters.

III-step: T-junction input is now supplied with DC power at 1V by the calibrator.

IV-step: the calibrator output is trimmed to V_{DC1} value until restoring the initial E_{1RF} output of the reference TVC. This obtained, an analogue operation is done on unknown device, restoring its initial output voltage E_{3RF} trough a V_{DC3} input.

Each RF-DC voltage substitution is always repeated with polarity exchange of the DC signals, so to compensate for the spurious thermoelectric effects of the contacts. The DC output values of the calibrators V_{DC1} and V_{DC3} are registered for further use. The steps I-IV are repeated several times at every measurement frequency, for generating a useful statistic. Measurement procedure can be now considered completed. Data elaboration and correction must however take place before obtaining the measurand, i.e. the transfer difference η_e of the power sensor.

5. DATA ELABORATION AND CORRECTION

With reference to the scheme of Fig. 1, we point out to the determination of three quantities, that is, the power sensor transfer difference δ_U and the RF input voltages V_1, V_3. However the last two are only apparent unknown quantities because can be obtained easily from the standard transfer difference δ_R and from the scattering parameters of the devices, which are independently measured aside. Due to the different electrical length of the devices and to the different input reflection coefficients Γ_1 and Γ_3, of course the RF voltages at their inputs are not the same and furthermore they are different from the RF voltage imposed by the generator in the reference plane of the T-junction. The two RF voltage are related by a the following formula:

$$\left|\frac{V_1}{V_3}\right| = \left|\frac{[1+\Gamma_3(S_{13}-S_{11})][1+\Gamma_1]}{[1+\Gamma_1(S_{13}-S_{11})][1+\Gamma_3]}\right|, \qquad (6)$$

where S_{11}, S_{13} are the scattering parameters of the symmetric T-junction. Derivation of (6) can be found directly in [12]. By using the same definition of transfer difference (2) or the modified form (4), we determine the value of the voltage V_1 at the input of the standard TVC:

$$V_1 = (\delta_R + 1)V_{DC1} \qquad (7)$$

This done, the RF voltage V_3 is calculated at the input of the power sensors under calibration, by substituting (7) in (6). The transfer difference δ_U of the same device is obtained by applying again the definition (2):

$$\delta_U = \frac{V_3 - V_{DC3}}{V_{DC3}}. \qquad (8)$$

Then, δ_U is converted to η_e trough (3), so obtaining a transfer power standard calibrated through RF voltages. Formula (3) requires the determination of the ratio r:

$$r = \frac{R_{RF}}{R_{DC}}. \qquad (9)$$

The measurement of the input DC resistance is quite trivial and is made with at four wires for obtaining the best accuracy. Instead the RF resistance has been obtained from the measurement of the input reflection coefficient Γ_3 by means the following formula:

$$R_{RF} = \frac{1-|\Gamma_3|^2}{1-2\,\mathrm{Re}(\Gamma_3)+|\Gamma_3|^2}. \qquad (10)$$

This calculation step is very critical from the accuracy point of view, cause some intrinsic limitation of network analyzer used to measure the input reflection coefficient Γ_3. Therefore the most significant uncertainty component of the calibration process hereby described will be related to the determination of term (10).

4. RESULTS

Last calibration of a thermoelectric power sensor, made between 1 kHz and 100 MHz in accordance to the mentioned scheme described, has produced results of Table 1 and 2.

Table 1. Comparison between the Reference TVC and unknown power sensor in term of Transfer Difference. Total Uncertainties $U\delta_R$, $U\delta_U$ are given at one standard deviation. Unknown TVC identifies with the thermoelectric power sensor under calibration.

	Reference TVC		Unknown TVC	
Freq. (kHz)	δ_R (ppm)	$U\delta_R$ (ppm)	δ_U (ppm)	$U\delta_U$ (ppm)
1	2	2	30	29
20	2	2	-36	29
50	2	2	-39	29
100	2	2	-49	29
300	2	2	-151	29
500	2	2	-239	29
1000	4	5	-289	30
3000	15	5	-345	43
10000	28	10	-1120	44
20000	80	40	-1200	59
30000	110	90	-1612	100
50000	320	250	-2018	253
70000	-350	500	-2174	502
100000	-1800	1000	-2344	1006

Table 2. Comparison between the RF Voltage Standard given in term of transfer difference and the RF Power Standard given in term of Effective Efficiency. Total Uncertainties Uδ_R, Uη_e are given at one standard deviation.

	RF Voltage. Stand.		RF Power Stand.	
Freq. (kHz)	δ_R (ppm)	Uδ_R (ppm)	η_e	U(η_e)
1	2	2	0.9999	0.00005
20	2	2	0.9999	0.00008
50	2	2	0.9996	0.00008
100	2	2	0.9994	0.00008
300	2	2	0.9992	0.00008
500	2	2	0.9992	0.00008
1000	4	5	0.9990	0.00008
3000	15	5	0.9967	0.00010
10000	28	10	0.9929	0.00011
20000	80	40	0.9909	0.00013
30000	110	90	0.9899	0.00021
50000	320	250	0.9893	0.00051
70000	-350	500	0.9892	0.00100
100000	-1800	1000	0.9891	0.00199

Figure 2 highlights a regular decaying trend of the RF Power standard versus frequency that is not detected when the same standard is obtained with the microcalorimeter technique. This happens because the microcalorimeter has not enough sensitivity below the frequency of 10 MHz, as already mentioned.

Table 2 and Fig. 2 shows that the typical effective efficiency values range with a regular trend from 0.9999 at 1 kHz to 0.9891 at 100 MHz. The related associated uncertainties are 5x10^{-5} and 20x10^{-4} at 1-standard deviation.

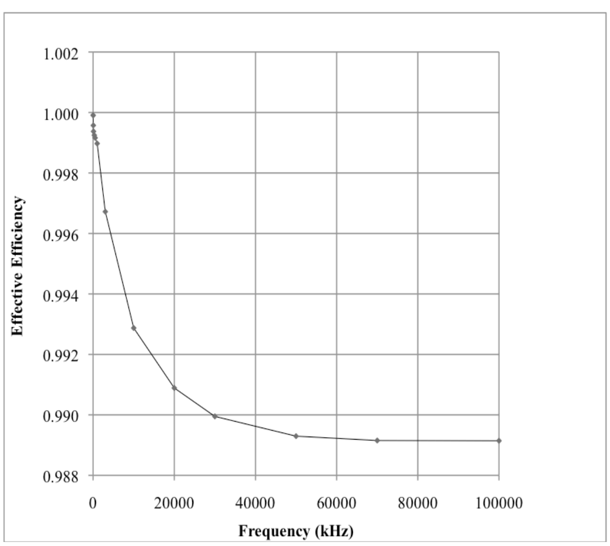

Fig. 2. Observed behaviour of the effective efficiency of a thermoelectric power sensor at low frequency.

4. STATISTIC AND ACCURACY ASSESEMENT

The evaluation of the uncertainties associated to each step of the whole calibration process is based on the assumption that any correlation exists among the quantities that must be measured for obtaining the final results, that is, the effective efficiency of a thermoelectric power sensor η_e. This assumption allows us to adopt the classical or Gaussian propagation of the errors in its simplest form, but in any case compliant to the rules given by the GUM [15].

The reference quantity involved in the calibration process is the transfer difference δ_R of the TVC that is identified with the RF Voltage Standard of INRIM in the frequency band 1 kHz - 100MHz. This device has an independent calibration certificate whose validity was assessed, during the participation to the key comparison CCEM.RF-K4.CL. The uncertainty values associated to the primary RF voltage standard (third columns of Table 1, 2) must be considered inclusive both of the type A and B components.

For all the measured quantities entering in the mathematical models defining the DUT calibration, the uncertainty is calculated as geometric mean of the standard deviation resulting by repeated measurements and the systematic term associated to the accuracy of the measurement instrument (e.g. nanovolmeter, impedance meter and network analyzer).

The only exception to this solution concerns the use of (6), which corrects the input RF voltage to the DUT for the effects of mismatches and of different electrical lengths of the devices connected to the lateral branches of the T-junction. Basically, it is assumed that the output of (6), that is V_3, has the same accuracy of the input quantity, V_1. This is consistent with the fact that an appropriate correction cannot reduce the accuracy of the data.

Each quantity involved in the process has been measured 10 times to deal with significant statistic. The most influent term in (3) or (5) on the measurand accuracy is the ratio R_{RF}/ R_{DC} which is determined with impedance meter at the lowest frequency whereas with vector network analyzer (VNA) at the others.

5. CONCLUSION

In this paper we describe the method to implement the RF power standard in the range DC - 100 MHz by means of RF-voltage measurements.

This method integrates the Microcalorimetric one, which fails to be effective below 10 MHz even when based on thermoelectric detectors. In this manner it is possible to obtain a real power sensor calibration at low frequency instead of data obtained by extrapolation.

Very important is the real measurement of η_e at 1 kHz that is a reference factor for the thermoelectric Microcalorimeter model [15].

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