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Realization and dissemination of high frequency power standard at INRIM

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ABSTRACT

In the High Frequency (HF) field, the primary power standard is maintained through reference sensors calibrated in terms of effective efficiency η_e. These devices are in turn used to transfer the power standard by means of direct comparison on the same matched generator. For this kind of operation, the only knowledge of the effective efficiency of the device is not enough and additional parameters of the reference sensor are necessary.

The paper describes the methods and techniques used at INRIM to disseminate the "HF power standard", with emphasis to all the technical aspects involved, in order to provide a thorough explanation of the procedures implemented.

1. Introduction

In the High Frequency (HF) domain the primary power standard is maintained using the microcalorimetric technique [1]. This technique allows to calibrate a reference sensor in terms of its effective efficiency η_e. The microcalorimeter is used only to realize the primary standard as the broadband measurements of η_e are very time consuming. For its dissemination, a different technique is used consisting in a direct comparison of the unknown sensor against the reference standard on the same matched generator. This process requires to know the reflection coefficient Γ of the reference sensor, and to measure a parameter called Voltage-Power Conversion Factor (VPCF), the meaning of which will be explained in the following. Both these parameters are used to obtain the Calibration Factor K of the Device Under Test (DUT) that is compared with the reference sensor.

The microcalorimetric technique has been widely described in the literature [2–6], whereas less importance has always been given to the additional measurements that are necessary to realize a primary standard effective for the dissemination process. The aim of the paper is to describe all the aspects of the primary power standard maintenance subsequent to its calibration in terms of effective efficiency that are, in any case, fundamental to complete the metrological reference chain for the HF-power quantity.

2. The effective efficiency measurements

The structure of the microcalorimeter used at INRIM has been already described in the literature by the same authors [7,8]. Basically, it consists of a twin coaxial line inset in a volume thermally insulated from the environment by three thermal shields. Two of the shields are passive, while the central one is active and controlled by a series of Peltier cells. Dedicated power sensors are placed at the end of the lines and the temperature difference between their input is measured through a thermometer that must be able to sense temperature differences of few mK or even less; this is the reason of a very complicated and sensitive temperature control of the whole system.

The device used as thermal load is a modified commercial sensor. The modification consists in removing the active electronic in order to read directly the sensor thermocouple by means of a nanovoltmeter. Fig. 1 shows

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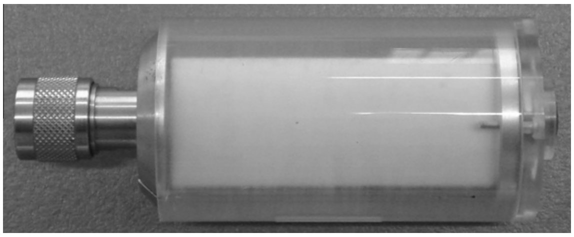

Fig. 1. Example of sensor used. It is a commercial sensor specifically modified removing the active electronic and directly reading its thermopile output. Here, it is shown after the modification placed inside the insulating mounting.

a modified power sensor fitted with type N connector, but similar devices are available with 3.5 mm or 2.92 mm connector, depending on the maximum frequency required.

All the measurement system is PC controlled via IEEE 488.2 GPIB bus by using a software that allows to automate completely the data acquisition procedure.

The asymptotic response of the system thermometer is related to the effective efficiency η_e, at the first order, by the following relation [8]:

$$\eta_e = \frac{e_2}{e_1 - e_{1SC}}, \tag{1}$$

where e_1 represents the asymptotic temperature reached by the DUT input when supplied with High Frequency (HF) power, e_2 the temperature measured when the HF power is substituted by a proper low frequency (LF) power, whereas e_{1SC} is the response when half of the HF power generating e_1 is supplied to a total reflective load. The term e_{1SC} is a correction related to the losses of the feeding lines. Other terms can be included in the equation to refine the model [9,10].

3. The standard transfer technique

The microcalorimetric measurement mentioned above provides the effective efficiency η_e of a sensor that becomes a reference sensor for disseminating the primary power standard to other laboratories.

The dissemination is made by means of a direct comparison on a matched generator between the reference standard and an uncalibrated power sensor that, in this case, becomes the DUT.

The measurand of the operation is the DUT Calibration Factor K which is defined as follows:

$$K = \eta_e(1 - |\Gamma|^2), \tag{2}$$

where η_e is the effective efficiency of the sensor and Γ is its reflection coefficient measured through a Vector Network Analyzer – VNA.

In the direct comparison, the unknown Calibration Factor K is computed by using the following equation [11]:

$$K_{UX} = \frac{M_{UX} \cdot P_{UX}}{M_{SX} \cdot P_{SX}} \cdot K_{SX}, \tag{3}$$

where K_{UX} is the Calibration Factor of the unknown, M_{UX} is the mismatch factor generator – DUT, P_{UX} is the power measured by the DUT, M_{SX} is the mismatch factor generator-reference standard, P_{SX} is the power measured by the reference standard and K_{SX} is the reference standard calibration factor derived from the effective efficiency measured with the microcalorimeter and by using (2).

Fig. 2 shows the measurement set-up: the generator that supplies the HF signal is connected to the reference sensor passing through a 10 dB PAD (Precision Attenuator Device) used to minimize the standing wave ratio, whereas the output of the sensor is read through a nanovoltmeter. Then the DUT is connected instead of the standard. Usually, it is a commercial sensor provided by a customer; its output is read through its mainframe that gives a response directly in terms of power.

The procedure has been implemented in order to repeat the measurement five times. The number of iterations has been chosen after several measurement cycles as the one that allows a good repetition of the results with minimum of time consuming. In any case it has been numerically verified that an increase of the repetition number does not affect substantially the standard deviation of the results. In more details, the calibration procedure follows the following sequences: the reference standard is connected to the system and the response recorded with the generator switched off; then the generator is set to the first required frequency and the reference standard output read; after that the generator is switched off again and the output of the reference standard read in order to have two zero points. The frequency is then set to the next value and the OFF–ON–OFF cycle is repeated. At the end of the frequency list, the standard is disconnected and substituted by the DUT and the same measurement sequence is repeated. The complete measurement of the reference standard and of the DUT is iterated five times to have a significant account of the connection–disconnection contribution. The power level of the generator output is 1 mW, the same used in the microcalorimeter.

At the end of the process, the relevant data will be the difference ON–OFF of the output level which is the signal directly linked to the power dissipated. If the devices are the commercial sensors that can be directly connected to the instrument mainframe, the output is read in terms of power and is compliant with (3). On the other hand, for the modified devices used as reference standard, the ON–OFF difference is a voltage level. It must be converted into a power level to insert in (3). This is possible only if the Voltage to Power Conversion Factor – *VPCF* is known.

A definition of the *VPCF* is given through in Fig. 3. The *VPCF* is the angular coefficient of the graph designed with the voltage readings on the x-axis and the corresponding powers on the y-axis, that is:

$$VPCF = \frac{\Delta P}{\Delta V} = \frac{P_2 - P_1}{V_2 - V_1}. \tag{4}$$

Since both the microcalorimeter and the comparison measurements are performed at the level of 1 mW, the two levels (0.9 mW and 1.1 mW) have been chosen as near as possible to this value.

The set-up for the VPCF measurement is shown in Fig. 4.

The measurement is performed in DC with the following steps: first of all the R_{DC} resistance of the DUT is

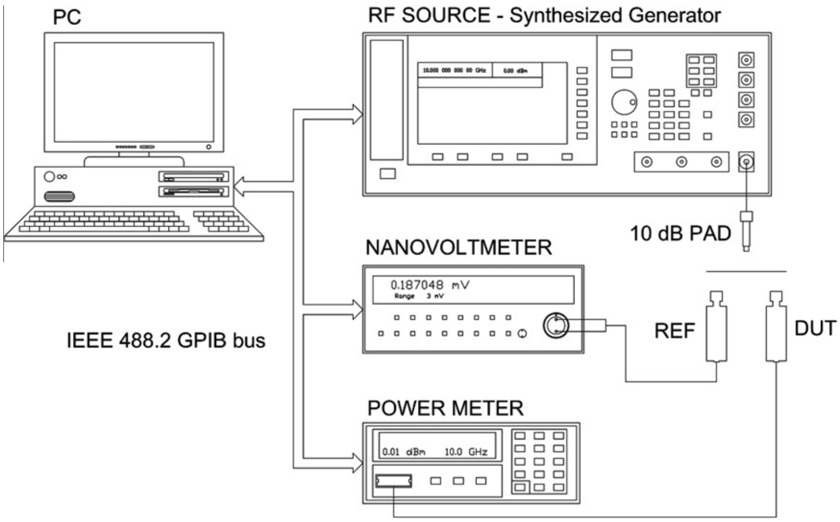

Fig. 2. Complete set-up for the dissemination measurements.

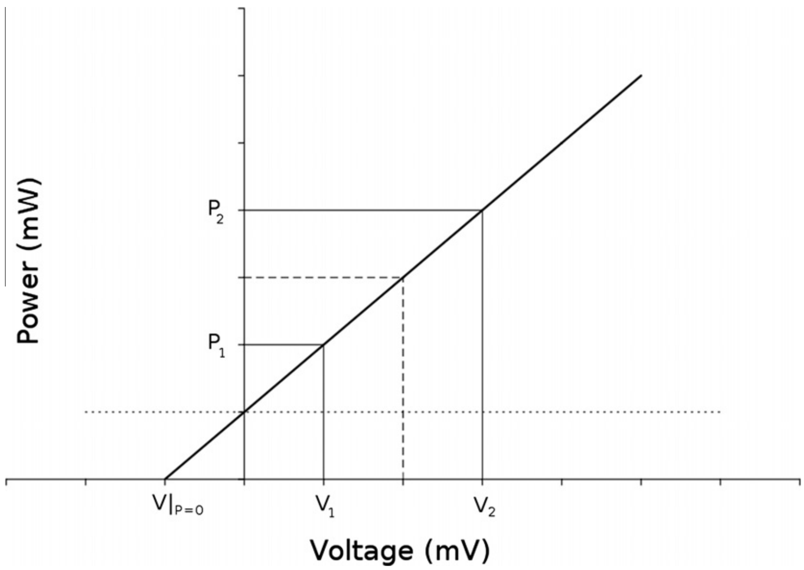

Fig. 3. Graphical definition of the *VPCF*.

measured using a four-wire configuration. From R_{DC}, the current necessary to have the power levels of 0.9 mW and 1.1 mW at the input port of the standard is computed. Then the computed nominal currents are sent to the device while its output voltage is read through a nanovoltmeter. The actual input power is computed through a current measurement as follows:

$$P = R_{DC} \cdot I^2. \tag{5}$$

The *VPCF* is given by:

$$VPCF = \frac{\Delta P}{\Delta V} = \frac{P_{1.1\ \mathrm{mW}} - P_{0.9\ \mathrm{mW}}}{V_{1.1\ \mathrm{mW}} - V_{0.9\ \mathrm{mW}}}, \tag{6}$$

where $P_{1.1\ \mathrm{mW}}$ is the actual power supplied at the level of 1.1 mW, $P_{0.9\ \mathrm{mW}}$ is the actual power supplied at the level of 0.9 mW whereas $V_{1.1\ \mathrm{mW}}$ is the *emf* output level read with the 1.1 mW power and $V_{0.9\ \mathrm{mW}}$ is the *emf* output level read with the 0.9 mW power.

Once the *VPCF* is known, the output voltage levels V_{SX} of the standard can be converted to obtain the values P_{SX} required in (3) using the equation:

$$P_{SX} = VPCF \cdot V_{SX}. \tag{7}$$

Actually the correct equation that should be used is the following one:

$$P_{SX} = VPCF \cdot V_{SX} + P|_0, \tag{8}$$

where $P|_0$ is the power level corresponding to the excess noise of the sensor. This can produce a straight line not passing through the origin of the axes and $P|_0$ in (8) ac-

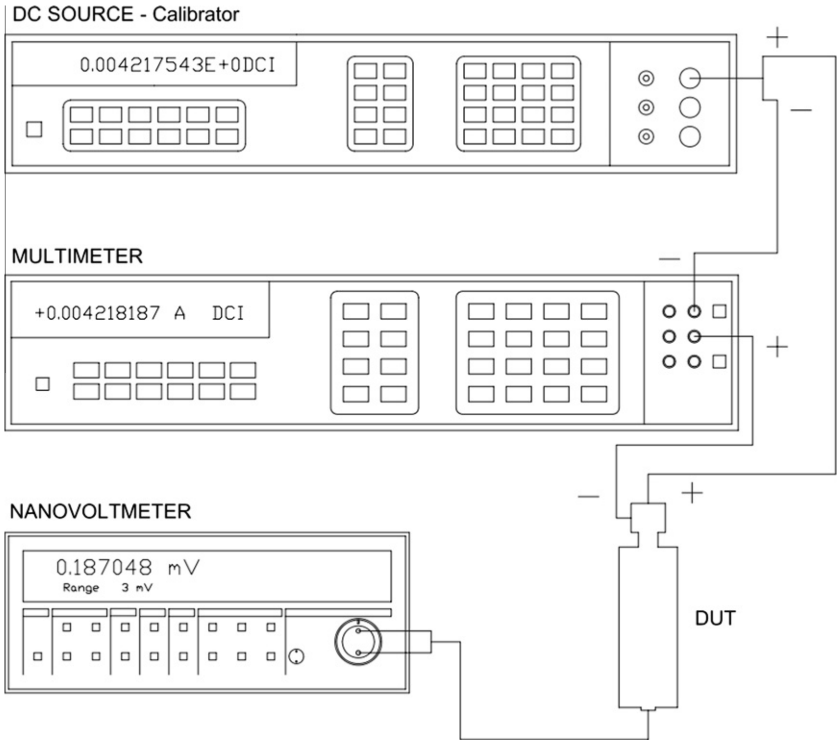

Fig. 4. Set-up for the evaluation of the *VPCF*.

counts also the noise when the sensor is not fed. It can be demonstrated that the signal is five order of magnitude greater than this noise and for this reason can be neglected.

Concerning the other quantities appearing in (3), K_{SX} is derived, as already said, through the effective efficiency measured in the microcalorimeter (2).

The mismatch factors M_{UX} and M_{SX} have the explicit expression:

$$M = |1 - \Gamma_L \Gamma_G|^2, \tag{9}$$

where Γ_L is the reflection coefficient of the power sensor and Γ_G is the reflection coefficient of the generator. The coefficient Γ_G cannot be directly measured but, since the sensor is connected to the generator through a 10 dB PAD, Γ_G can be, at the first order, replaced by the reflection coefficient Γ_P of the PAD. Normally the quantities M_{UX} and M_{SX} are assumed equal to 1 with an uncertainty computed as [11]:

$$u_M = \sqrt{2} \cdot \Gamma_L \cdot \Gamma_P. \tag{10}$$

In all the measurement procedure, a not trivial task is the computation of the uncertainty of the single elements measured and of the final result.

Concerning the determination of the *VPCF*, all the instruments used to obtain data, that is, the DC Resistance R_{DC}, the current I and the voltage output V are traceable to the primary standards of resistance, current and voltage. Furthermore, all these data are obtained computing a mean value of repeated measurements. For this reason the uncertainty associated to the final results is a square sum of the mean standard deviation computed on the repeated measurement (σ_{m_i}) plus the uncertainty provided by the instrument manual[1] (u_{man_i}) that is:

$$u_i = \sqrt{\sigma_{m_i}^2 + u_{man_i}^2}, \tag{11}$$

where i stands for the resistance, the current or the voltage, appropriately.

The uncertainties on the ΔP, ΔV and *VPCF* are obtained according to the GUM [12].

The uncertainties of the quantities appearing in (3) comes from different evaluations, and their types, defined in accordance with the GUM [12], are presented in Table 1.

The uncertainty of P_{UX} depends on the repeated measurements and on the instrument used and is evaluated as a square sum of these two contributions. P_{SX} uncertainty is evaluated, according to the GUM [12], by applying the

Table 1
Sources of uncertainty in the determination of K_{UX}. A and B are the uncertainty types defined in accordance to the GUM [12].

Parameter	Symbol	Type
M_{UX}	$u_{M_{UX}}$	A + B
M_{SX}	$u_{M_{SX}}$	A + B
P_{UX}	$u_{P_{UX}}$	A + B
P_{SX}	$u_{P_{SX}}$	A + B
K_{SX}	$u_{K_{SX}}$	A

[1] The 1 year manufacturer uncertainty is provided as a percentage on the reading plus a percentage on the scale.

error propagation in (7). The K_{SX} uncertainty depends on the uncertainty of η_e, obtained with the microcalorimeter, and on the uncertainty of Γ, measured with the VNA, according to (2).

If the two power sensors have different connector types, then an adapter must be used to allow the comparison. This interface must be characterized in order to correct the measurements for the additional losses introduced. These are evaluated in terms of the transmission coefficient A that is measured in linear magnitude using a VNA. Knowing the attenuation coefficient, it is possible to correct for the actual value of P_{SX} by using the following equation:

$$P_{SX} = \frac{P_{SX}^{row}}{A}, \tag{12}$$

where P_{SX}^{row} is the measured value of P_{SX}. A consequence of this computation, is that the uncertainty on P_{SX} depends also on the transmission coefficient A.

4. Example of results

As an example, the results of a calibration will be shown of a power sensor equipped with a type N connector, against a reference standard equipped with a 3.5 mm connector. In Fig. 5 the Calibration Factor K_{UX} is shown. The two series represents the same results, but with different uncertainties: full square is relevant to the results with the uncertainties evaluated from the data collected, while the empty square represents the results with the uncertainties declared in the Calibration and Measurement Capabilities – CMCs of the BIPM. As it can be seen, the uncertainties evaluated are lower than the official ones declared, and this is the consequence of hardware improvement made in the last years [13,14]. The improvements regard different aspects: firstly CMCs were declared using primary standard of the bolometric type measured through resistive Wheatstone bridge while the reference used now is a thermoelectric power sensor directly measured by means of a nanovoltmeter. Moreover also the microcalorimeter itself has been changed. A Peltier controlled microcalorimeter is used instead of a water bath less efficient system.

Fig. 6 represents the uncertainty budget for the quantity K_{UX}. The quantities shown are the uncertainty components defined as the sensitivity coefficients (see [12], paragraph 5.1.3) multiplied by the uncertainty of each element u_i:

$$u_i' = \frac{\partial K_{UX}}{\partial i} u_i, \quad i = M_{UX}, M_{SX}, P_{UX}, P_{SX}, K_{SX}. \tag{13}$$

The sensitivity coefficients are presented in Table 2. In Fig. 6 all the quantities with the exception of $u_{K_{UX}}$ are expressed in absolute value. In fact $u_{K_{UX}}$, that is the uncertainty of the quantity K_{UX}, is always positive by definition. On the other hand, the other quantities are the sensitivity coefficients used to compute K_{UX} itself and they can be either negative or positive. In the computation of K_{UX} they are squared summed, so, only their absolute value is significant.

It can be seen that the main contributions came from P_{SX} and P_{UX}. This is due to the fact that the instrument used to measure P_{UX} has not a good resolution, leading to a final uncertainty quite big, while, concerning P_{SX}, this element is obtained through an indirect procedure, with an uncertainty dependent from different parameters. The uncertainty budget of P_{SX} is represented in Fig. 7 which shows that main error contributions came from the *VPCF* and the attenuation factor of the adapter. This last is also responsible of the worsening of the final uncertainty of P_{SX} and consequently of K_{UX} at higher frequencies. Indeed all the scattering coefficients of the adapter worsen for frequencies higher than 2 GHz. The quantities shown are the uncertainty components defined as the sensitivity coeffi-

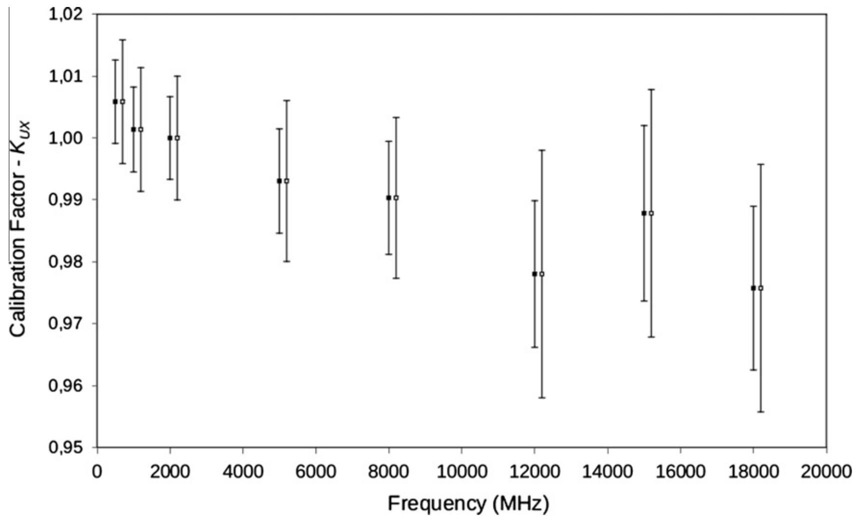

Fig. 5. Results of the Calibration Factor K_{UX} evaluated for a sensor equipped with type N connector against a 3.5 mm reference standard. Full square represents the results with the uncertainties evaluated from the data collected, while empty squares represents the results with the uncertainties declared in the CMCs.

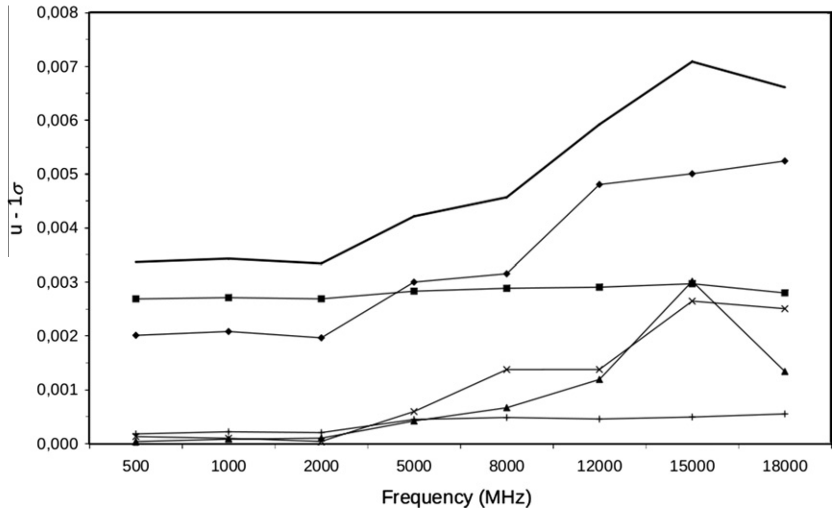

Fig. 6. K_{UX} uncertainty budget: the straight line represents $u_{K_{UX}}$. The other lines represent the contributions of each element expressed in absolute value as defined in (13): full square is $u'_{P_{UX}}$, full diamond is $u'_{P_{SX}}$, full triangle is $u'_{M_{UX}}$, cross is $u'_{M_{SX}}$ and vertical segment is $u'_{K_{SX}}$.

Table 2
Sensitivity coefficients in the error propagation of K_{UX}.

Quantity	Sensitivity coefficient
M_{UX}	$\frac{\partial K_{UX}}{\partial M_{UX}} = \frac{P_{UX} \cdot K_{SX}}{M_{SX} \cdot P_{SX}}$
M_{SX}	$\frac{\partial K_{UX}}{\partial M_{SX}} = -\frac{M_{UX} \cdot P_{UX} \cdot K_{SX}}{P_{SX} \cdot M_{SX}^2}$
P_{UX}	$\frac{\partial K_{UX}}{\partial P_{UX}} = \frac{M_{UX} \cdot K_{SX}}{M_{SX} \cdot P_{SX}}$
P_{SX}	$\frac{\partial K_{UX}}{\partial P_{SX}} = -\frac{M_{UX} \cdot P_{UX} \cdot K_{SX}}{M_{SX} \cdot P_{SX}^2}$
K_{SX}	$\frac{\partial K_{UX}}{\partial K_{SX}} = \frac{M_{UX} \cdot P_{UX}}{M_{SX} \cdot P_{SX}}$

Table 3
Sensitivity coefficients in the error propagation of P_{SX}.

Quantity	Sensitivity coefficient
$VPCF$	$\frac{\partial P_{SX}}{\partial VPCF} = \frac{V_{SX}}{A}$
V_{SX}	$\frac{\partial P_{SX}}{\partial V_{SX}} = \frac{VPCF}{A}$
A	$\frac{\partial P_{SX}}{\partial A} = -\frac{VPCF \cdot V_{SX}}{A^2}$

cients (see [12], paragraph 5.1.3) multiplied by the uncertainty of each element u_i:

$$u'_i = \frac{\partial P_{SX}}{\partial i} u_i, \quad i = VPCF, V_{SX}, A. \tag{14}$$

The sensitivity coefficients are presented in Table 3. In Fig. 7 all the quantities with the exception of $u_{P_{SX}}$ are expressed in absolute value for the same reasons of Fig. 6.

Since this technique allows to obtain the Calibration Factor K of an unknown sensor comparing it against a reference standard directly calibrated into the microcalorimeter, the uncertainty obtained is higher than the one of the microcalorimeter itself [15]. Despite this, the technique

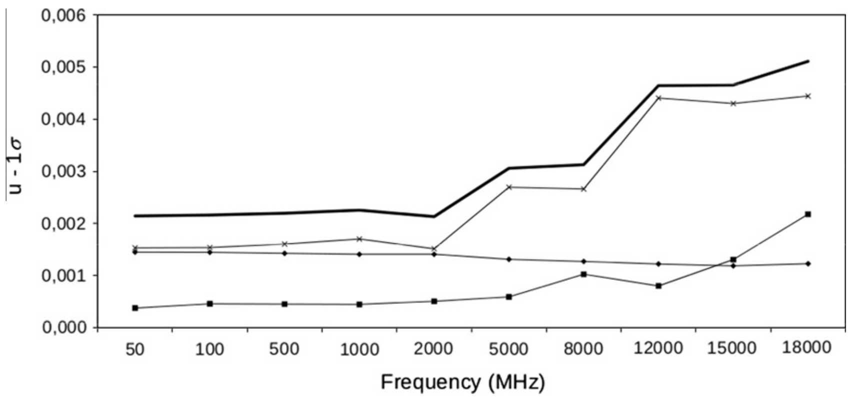

Fig. 7. P_{SX} uncertainty budget: the straight line represents $u_{P_{SX}}$. The other lines represent the contributions of each element expressed in absolute value as defined in (14): full square is $u'_{V_{SX}}$, with V_{SX} sensor output voltage, full diamond is u'_{VPCF}, and cross is u'_A.

has been already used also in international comparisons providing good results [16].

5. Conclusion

In the paper, a complete description of the process used at INRIM to disseminate the high frequency power standard has been provided. Different aspects have been described enlightening the criticalities of the procedure. First of all there is the need of the definition and evaluation of the quantity called Voltage-Power Conversion Factor – *VPCF* that is fundamental to completely describe the reference standard. The description of the measurement and computation of this factor has been provided together with the evaluation of its uncertainty.

The dissemination technique has been described together with the measurement set-up used and the related uncertainty budget has been shown.

This process provides, as a result, the Calibration Factor *K* of an unknown sensor comparing it against a reference standard directly calibrated into the microcalorimeter. Despite the final uncertainty obtainable with this method is higher than the one of the microcalorimeter, this technique has been already used also in international comparisons, because it can applied to every type of power sensors.

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