ACCURACY ASSESSMENT IN HF POWER METER CALIBRATION

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Abstract - *The paper analyses the classical procedures have to be performed for calibrating power meters having coaxial power heads. These procedures are intended for commercial power meters used by all measurement laboratories, nevertheless they include references to the specific measurement set-up used by the Italian primary measurement laboratory, that is IEN. The paper is aimed to provide technical documentation, that eases the unification of the measurement accuracy assessment in all the laboratories accredited or requiring accreditation by Italian calibration service (SIT).*

Keywords - HF power, standards, calibration, accuracy.

1. INTRODUCTION

Modern commercial power meters for high frequency (HF) are voltmeters coupled to sensors that convert HF power to a dc-voltage. All power sensors may be arranged by two classes, i.e. true rms-value detectors like bolometers and thermocouples, or instantaneous-value detectors like diodes.

Bolometers are dc-biased resistive elements working on the equivalence principle of the thermal effects, intrinsic to the dc-substitution method [1]. This reduces HF power measurement to that of a fundamental SI quantity, i.e. the direct current. Bolometer dynamic range is no wider than 20 dB, with the best performances in the range 1-10 mW. Bolometers are no longer of great interest for commercial applications, while confirm to be fundamental devices for realisation of the HF primary power standards.

Thermocouples are detectors based on the well know thermoelectric effect, that is dc-voltage generation between two junctions of different materials when are under a temperature gradient. These detectors are cascaded by chopper and ac-preamplifier cause their outputs are very low (nV or µV). Thermocouple power sensors have a wider dynamic range if compared to the bolometer detectors; typically from -30 dBm to 20 dBm, that is the square low region of the actually used semiconductor thermocouples. The most noticeable features of the thermocouple sensors are their independence of the absolute temperature, cause their nature of differential system.

Diode sensors convert high frequency power to dc-voltage because of their rectification properties, which arise from the non-linear current-voltage characteristic. This one is typically an exponential function, approximated to a parabolic function if the applied signals are below a level specific. With this condition verified, the output signal is proportional to the square of the input wave amplitude, that is, to the power. Like thermocouples, diode power sensors are cascaded, for the same reason, by a chopping system and ac-preamplifier. The most important properties of the diode are the low time constant and the high sensitivity, which make the diode sensor suitable for high frequency wave sampling. The useful dynamic spans from -70 dBm to -20 dBm. Recently new diode detectors have been introduced with an extended range to +20 dBm, but at the expense of the linearity. This paper describes the calibration techniques applied to the most used HF power meters, therefore less common or more specialised instrumentation like calorimeters, Golay's cells, electron beam wattmeters or piroelectric devices are deliberately not considered.

2. POWER METER STRUCTURE

Commercial power meters based on thermocouple and diode detectors have the structure of Fig.1.

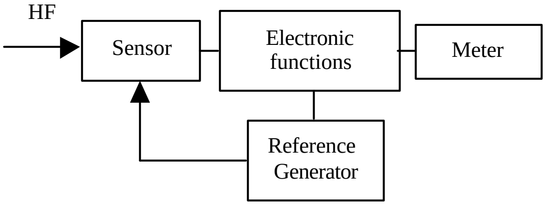

Fig.1: Power meter based on thermocouple or diode detectors.

The power meter consists of a sensor, an electronic mainframe and a 50 MHz reference generator. The low-level dc-output signal of thermocouple or diode sensor is chopped and preamplified directly in power head. Then, it is directed to an electronic main frame where it is filtered, synchronously detected and finally displayed by a digital meter. The main frame provides also important auxiliary functions like reference oscillator control, correction for sensor calibration factor, sensor auto-recognising. Modern mainframes work both with thermocouples and diodes, being able to provide different settings of the electronic. Power head is an

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analogical device, but most recent models include also a digital memory storing characteristic data, like calibration factors, temperature coefficients and linearization curves. These data are used by the internal processor for improving the measurement accuracy and are updated, even if not yet friendly, as part of the calibration process of the head. Power meters based on bolometers have a more simple structure. They are reducible to a self-balancing loop that biases the bolometer with a fixed dc-power level as Fig.2 shows. When the HF power is applied to the detector, the bolometer warms and its resistance changes. This unbalances the circuit, typically a Weatstone bridge, and produces a differential input to the amplifier whose feedback reduces the dc-bias up to restore the initial thermal equilibrium. By virtue of the principle of the equivalence of the thermal effects, the HF power supplied to the bolometer mount should be equal to the withdrawn dc-power, that is measured by a dc-meter. In practise the dc-substitution is not exact, cause the parasitic losses, in the mount, that do not produce resistance change. The mount is said to have an effective efficiency less than 100% and it must be determined at each measurement frequency for considering the sensor calibrated.

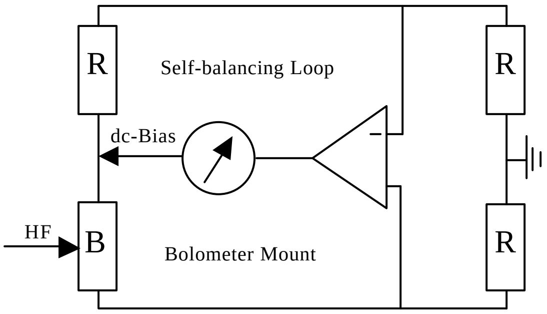

Fig.2: Scheme of a bolometric power meter.

Effective efficiency measurement of bolometer mounts is the essential step in the realisation of the HF power standard. Measurement is made directly with the microcalorimeter [1], a measurement system used only by primary laboratories.

3. THEORETICAL BACKGROUND

A HF power measurement is always reducible to the determination of the power output at a port of an electric circuit. This is indicated as equivalent generator and its best description is done by the transmission line theory [3].

In [3], the wave amplitudes assume the role of currents and voltages. On a generic i-th port these are incident (a_i) or emergent (b_i), while the reflection coefficients Γ_i defined as b_i / a_i substitute the impedances. A HF source is represented by:

$$b_G = b_S + \Gamma_G a_G \quad (1)$$

where b_G is emergent wave from source, a_G incident wave on the same, b_S the wave really generated inside the source and Γ_G the reflection coefficient. Γ_G and internal impedance Z_G of a source are related by:

$$\Gamma_G = (Z_G - Z_0)/(Z_G + Z_0) \quad (2)$$

being Z_0 the normalisation impedance, usually coincident with the characteristic impedance of the line to which the source is connected. For a generic load of impedance Z_L, the related reflection coefficient Γ_L is given by (2), by substituting Z_L to Z_G. It is now important to write the power transfer relation from generator to load when they are connected through a transmission line of characteristic impedance Z_0, like Fig.3 shows. Being the HF power equal to the modulus square of the wave amplitudes, if these ones are normalised to the characteristic impedance value of the transmission line, we can write that the emerging power from generator port is $P_G = |b_G|^2$, while the incident power on the load Z_L is $P_I = |a|^2$. With reference to Fig.3, the expression holds:

$$P_L = |b_S|^2 \left(1 - |\Gamma_L|^2\right) / |1 - \Gamma_G \Gamma_L|^2 \quad (3)$$

where P_L is the power absorbed in the load, while $|b_S|^2$ is the power really generated inside the generator port. This term coincides with the power delivered by the generator to a perfectly matched load, that is, load impedance equal to the characteristic impedance Z_0 of the transmission line. The formula (3) may be used to characterise univocally the same generator in terms of power. Another load condition, worthy to be mentioned, is when the load impedance is equal to the complex conjugate impedance of the generator. The generator is said *conjugately matched* and it supplies the maximum available power P_{AV}:

$$P_{AV} = |b_S|^2 / \left(1 - |\Gamma_G|^2\right) \quad (4)$$

Equations (3), (4) are fundamental for HF circuit theory, playing the same role the Ohm low has for the dc and low frequency. If the load is a power sensor, (3) provides a relation between the power supplied by the generator and that measured by the power meter.

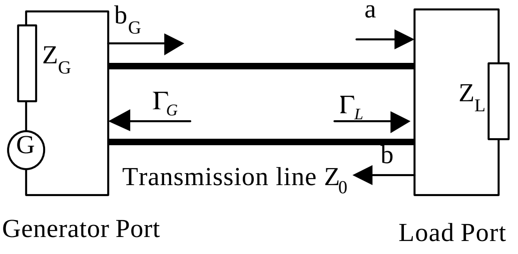

Fig.3: Generator-load connection through a line of impedance Z_0.

4. POWER METER CALIBRATION

The calibration of bolometric power meters consists in the determination of power sensor calibration factor defined by:

$$K = \eta\left(1 - |\Gamma|^2\right) \quad (5)$$

where η is the effective efficiency of the sensor, that is, *the ratio dc-substituted power to total dissipated power in the* *bolometric mount*. Γ is reflection coefficient of the power sensor connected to the meter.

The calibration for defining the primary power standard is in two steps and consists in measurement of η with microcalorimeter and Γ with vectorial network analyzer (VNA).

A more direct measurement procedure compares the unknown against a standard after having alternatively connected the two sensors to a non-reflecting generator port. In practise, this method is difficult to use, because it requires to match the generator port or with manual tunings or with levelling loop [1]. Manual tuning is very time consuming and not frequency agile, while source levelling requires high performance hardware. Therefore, the alternative comparison method with resistive power splitter is mostly adopted.

For power meters based on thermocouple or diode sensors, calibration means still determination of the calibration factor, but the procedure is a little bit more complicated and requires an additional note. Indeed, in these power meter types, the calibration factor curves may be arbitrarily shifted acting on the amplifying section of the meter. Normally, this is done during the initial setting of the instrument, when the sensor is connected to the internal reference source (e.g. 1 mW at 50 MHz). At the reference frequency the typical calibration factor selected is equal to 100% and is named *reference calibration factor.*

The operator may adopt any value, but have to indicate explicitly it in calibration report; otherwise, he will create a misleading interpretation of the calibration data. The calibration of the power meter is also dependent on the quality of the reference source, whose characterisation must therefore be entered in the calibration procedure of the instrument. This is an additional step not necessary for the power meters based on bolometer sensors.

For power meter based on thermocouple and diode sensors the European co-operation for Accreditation (EA) Organisation suggests the following definition of the calibration factor K_X :

The ratio of incident power P_{IR} *at the reference frequency to the incident power* P_{IX} *at the calibration frequency under the condition that both powers give the equal sensor response, all multiplied for the reference calibration factor* K_R *chosen*, that is:

$$K_X = K_R \left(P_{IR} / P_{IX} \right) \qquad (6)$$

In the experimental set-up that implements (6) the power meter under test should work like a zero meter, comparing two incident power levels supplied by calibrated generators. These are not available in practise; therefore, the given definition may not be implementable experimentally.

Realistically, it is necessary to relay on an instrument set-up in which a not calibrated, but enough stable generator may be switched between unknown and standard power meter or may supply them contemporary the same power level both at test frequency and reference frequency. With reference to the set-up scheme of Fig.4, we write:

$$\frac{M_{UX} P_{UX} K_{UR}}{M_{UR} P_{UR} K_{UX}} = \frac{M_{SX} P_{SX} K_{SR}}{M_{SR} P_{SR} K_{SX}} \qquad (7)$$

where the terms $P_{UR}, P_{UX}, P_{SR}, P_{SX}$ mean the effective powers measured by unknown (subscript U) and standard power sensors (subscript S) at the text (subscript X) and reference frequency (subscript R) respectively, while the terms $M_{UR}, M_{UX}, M_{SR}, M_{SX}$ are the mismatch factors related to the reflection coefficients of the generator (Γ_G) and power sensors (Γ_U, Γ_S). Symbols $K_{UX}, K_{UR}, K_{SX}, K_{SR}$ represent the calibration factors of the unknown and standard power sensors as given by (5). Furthermore it is useful to remember, that (7) is also equal to P_X / P_R that is the ratio of the available powers at the generator, respectively at the test and reference frequency. From the relation (7), we can still obtain the EA given definition of calibration factor but in a more useful form for the accuracy assessment:

$$K_{UX} = K_{UR} \left(\frac{M_{UX}}{M_{UR}} \frac{P_{UX}}{P_{UR}} \right) \left[\frac{M_{SR}}{M_{SX}} \frac{P_{SR}}{P_{SX}} \frac{K_{SX}}{K_{SR}} \right] \qquad (8)$$

Indeed, (8) reduces to (6) if we hypothesise to supply the standard power meter with the same power level at the text and reference frequency, (factor in square bracket equal 1).

This demonstration justifies the EA definition, but also introduce explicitly all the quantities that play role in the accuracy assessment of the measure.

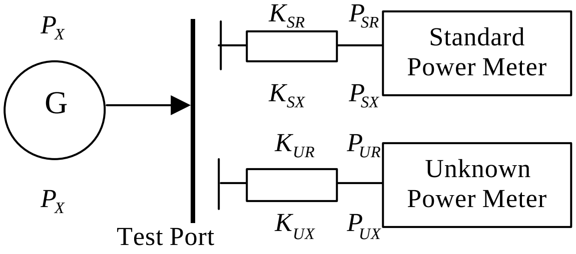

Fig.4: Scheme of a real calibration set-up power meters

5. CALIBRATION PROCEDURE

The most used experimental set-up for a direct calibration, is based on a resistive power splitter, whose merits and limits are well known in the literature [4]. Such a set-up is also considered, in the version Fig.5 shows, for an example of accuracy assessment by [5]. The main feature of this scheme is the broadband capability. Furthermore the scheme of the Fig.5 is suggested as a remedy to the problem of the mismatch. Indeed, it could be demonstrated that the two-resistor power splitter realises an improvement of the source match if used in power levelling loop or in power ratio measurements.

Power levels measured by the unknown and standard power meters at the test port are therefore normalised to the measurement of the uncalibrated power meter permanently connected to the reference port.

Measurement steps are very simple. Indeed, after complying with the initial setting procedures, typical of each power meter involved in the calibration process, the operator have to connect and disconnect alternatively the *unknown* and *standard power meter* at the test port and to register the power levels $p_{UR}, p_{UX}, p_{SR}, p_{SX}$ which are normalised to the power level on the reference channel.

Initial setting of each power meter must be carefully done according to the specific user manuals. I point out only some steps of the initial setting that are more critical:

1- selection of the reference calibration factor.
2- sensor check and adjusting using 1 mW reference source.
3- updating calibration factor list of the standard.
5- deselecting calibration factor list for the unknown.
6- power sensor zeroing at each frequency change.

The steps 1, 2 are not applied to power meters that use bolometer sensors, while the others are optional for the power meter on the reference channel, which is only requested to be very stable. The experimental set-up of Fig.5 could be simplified without loosing performances. Unknown and standard have just to be connected at the power splitter branches [4]. The operator has to take only simultaneously their outputs and combines them into ratios. To compensate the power splitter asymmetry, anyway the position of the sensors must be rotated by taking always the medium values of two measurements. Concerning the mismatch, nothing is changed as still ratio measurements are performed by means a two resistor power splitter [4].

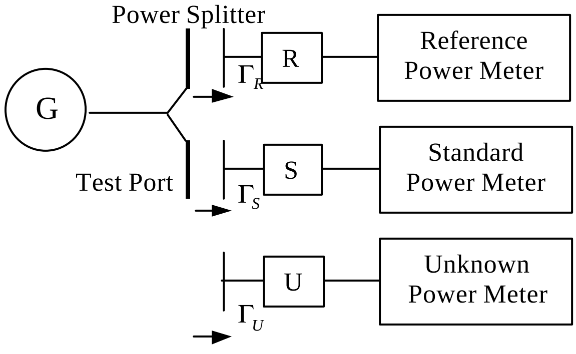

Fig.5: Scheme of the measurement set up proposed by EA-02-S1.

6. ACCURACY ASSESSMENT

The accuracy assessment of the calibration measurements follows the leading line suggested by [5], with some variation that will be commented including experimental results. The scheme of Fig.5, good in line of principle, is worsened by the real imperfections of the power splitter. When its symmetry is not perfect, the error contribution of the generator reflection coefficient is present and may be huge. Furthermore, the poor insulation between the output channels introduces noticeable mismatch errors when standard and measurand have bad input reflection coefficient [4]. The measurement set-up I use is shown in Fig.4, while accuracy assessment is based on (8) relating the output quantity K_{UX} to the input quantities:

$$K_{UR}, K_{SR}, K_{SX}, P_{UR}, P_{UX}, P_{SR}, P_{SX}, M_{UR}, M_{UX}, M_{SR}, M_{SX} \quad (9)$$

Equation (8) being rational, the total uncertainty ΔK_{UX} on the measurand K_{UX}, assumes a simple expression if the uncertainty on all input quantities (9) is took as relative, that is:

$$\Delta K_{UX} = \sqrt{\Delta K_{UR}^2 + \Delta K_{SR}^2 + ... + \Delta M_{SX}^2} \quad (10)$$

The uncertainty terms ΔK_{UR} and ΔK_{SR} are related to the output level uncertainty of the reference sources used for initial setting of the power meters, if this is necessary. For bolometric power meters this terms do not exist.

The term ΔK_{SX} concerns the standard sensor and is deduced by its calibration certificate data, considering their probability distribution normal. Reference [5] suggests introducing a correction δK_{SX} to the input quantity K_{SX}. This should account for the drift of the standard between two consecutive calibrations. Power sensors, anyway have proved to be very stable standards, therefore the operation appears too conservative. The terms $\Delta P_{UR}, \Delta P_{UX}, \Delta P_{SR}, \Delta P_{SX}$ come directly from the instrument readings $P_{UR}, P_{UX}, P_{SR}, P_{SX}$ supposed normally distributed. These uncertainty terms contain a type A component due to the repeated measurements and a type B component due to the linearity of the meters. To comply with statistical rules a congruous number of repeated readings is necessary. Ten measures for every connection, each one repeated ten times, both for standard and for measurand, should provide a good statistic. Such a number of data should provide mean estimators that include as well system instability as connector repeatability. Furthermore, the available freedom degrees (10) should allow adopting a coverage factor of 2, as [5] recommends.

Unfortunately, this process is only possible, but not realistically applicable always. The reason is the short life of the metrology graded connectors which support a limited number of connections (more or less 500, for the PC3.5mm type, e.g.). A clever operator looking for a good statistic degrades rapidly both the measurand and particularly the measurement set-up. About this problem [5] does not give comments and suggestions.

From the mismatch factors $M_{ij}\,(ij = UR, UX, SR, SX)$, which follow a U-shaped probability distribution [6], the main contributions to the total uncertainty may arise. Cause the impossibility to know completely the refection coefficient Γ_G at the test port, M_{ij} may only be seen as input quantity whose limits of deviation are $M_{ij} = 1 \pm 2|\Gamma_G||\Gamma_{ij}|$. According to criteria of [6], the related uncertainty terms will be given by $\Delta M_{ij} = \pm 2|\Gamma_g||\Gamma_{ij}| / \sqrt{2}$.

The following experimental results are aimed to highlight both the cautions necessary with the calibration set-up previously discussed and with recommendations of [5]. Two bolometric sensors have been calibrated by means of microcalorimeter and VNA. Afterward, one sensor (unknown) has been compared against the other (standard), using both the schemes of Fig.4 and Fig.5 at the power level of 1 mW. The 18 GHz frequency is considered, because at this frequency, the power splitter used exhibits asymmetry and both power sensors have poor reflection coefficients. All these conditions highlight the drawbacks of calibration set-up used, indeed. The boundary conditions of the comparison are in the following table:

Measurement Frequency 18 GHz	
Standard Cal. Factor K_S	0.945±0.38% (k=2)
Standard Refl. Coefficient Γ_S	0.081
Unknown Cal. Factor K_U	0.927±0.38% (k=2)
Unknown Refl. Coefficient Γ_U	0.128
Test Port Refl. Coefficient Γ_G	0.099

Table 1: Characteristic data of the instrument set-up

Dealing with bolometric power sensors, the concepts of reference frequency and related quantities $K_{SR}, K_{UR}, M_{SR}, M_{UR}$ do not need consideration. The scheme of Fig.4 produces the uncertainty budget of table 2, while the scheme of Fig.5 produces the budget of table 3:

Input Quantity	*Extimate*	*Standard Uncertainty*	*Uncertainty Contributions*
K_S	0.945	0.0019	0.0020
M_S	1	0.0011	0.0011
M_U	1	0.0181	0.0181
P_S	0.952	0.0014	0.0015
P_U	0.942	0.0021	0.0022
K_U	0.935		0.0184

Table 2: Uncertainty budget relative to the scheme of Fig.4.

Input Quantity	*Estimate*	*Standard Uncertainty*	*Uncertainty Contributions*
K_S	0.945	0.0019	0.0020
M_S	1	0.0011	0.0011
M_U	1	0.0181	0.0181
p_S	0.938	0.0016	0.0017
p_U	0.929	0.0026	0.0026
K_U	0.936		0.0186

Table 3: Uncertainty budget relative to the scheme of Fig.5.

The given results come from 10 different sets of repeated measurements. The uncertainty contributions are relative terms to make usable (10) in total uncertainty calculation on the measurand K_U. Metered power levels in table 3 are normalised to the power level (1 mW) on the reference channel.

The two different schemes produce results significantly different from the expected value of K_U, which is independently known, even thought congruent, cause the large values of the resulting total uncertainty.

The set-up of Fig.5 seems produce a little bit better response in term of mean value but it is a little bit worst in term of total uncertainty. Anyway, the differences are not significant. The deviation of the mean values from the expected value of K_U reported in table 1 (about 1%) is a matter of fact and may only attributed to the poor reflection coefficient combination present in both schemes used. An improvement is only possible substituting, the power splitter with another one having better symmetry, so to minimise the effect of the Γ_G. Otherwise, good results are possible only on power meters having low reflection coefficients.

The scheme of Fig.5 has a worst accuracy budget because it must include the contribution of the reference power meter.

7. CONCLUSION

The comparison method based on resistive power splitter has been re-examined critically from the measurement uncertainty point of view. It is widely used by all calibration laboratories and holds of course its validity, but need caution when the reflection coefficient of the devices is not good. Results significantly different from the real one may be obtained, mainly due to the mismatch terms. Anyway, small differences in the instrument set-up may produce unexpected discrepancies in the uncertainty budget, so a critical revision of [5] should be considered. What is not acceptable in HF calibration is the high number of repeated connections. These, necessary to comply with the laws of the statistic [7], produce an abnormal tear and wear of the connectors with permanent damage of the instrumentation. Therefore, the uniformity of the accuracy assessment needs practical agreements beyond the theory.

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