XVIII IMEKO WORLD CONGRESS
Metrology for a Sustainable Development
September, 17 – 22, 2006, Rio de Janeiro, Brazil

CALIBRATION CONCEPT OF MODERN POWER METERS

Luciano Brunetti [1], *Luca Oberto* [1, 2], *Emil Vremera* [3]

[1] Istituto Nazionale di Ricerca Metrologica (INRiM), Strada delle Cacce 91, 10135 Torino, Italia, *brunetti@ien.it*
[2] Politecnic of Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italia, *oberto@ien.it*
[3] Technical University of Iasi, Bld. Dimitrie Mangeron 53, 700050 Iasi, Romania, *evremera@ee.tuiasi.ro*

Abstract: The power is the most important electromagnetic quantity from the metrological point of view, and for this reason the calibration techniques of high frequency power meters require a specific attention. Literature still refers to power meters of bolometer type, instruments that are mainly used almost only in the primary laboratories. Definitions, procedures, and calibration techniques elaborated for this instrument type must be adjusted before being applied to actual power meters, which work on different principles. Otherwise, inconsistent calibration results may be produced. This paper is aimed to ease the work of the laboratories that perform power meter calibrations from dc to 50 GHz, by elaborating on some technical aspect not well considered in the specialized literature.

Keywords: standard, power, calibration, microwave.

1. INTRODUCTION

Electromagnetic power is very important, because, from theoretical point of view, it is always a well definite quantity and in practice it is measurable even at high frequency (HF). Power measurement is a relatively easy exercise, particularly if done on coaxial transmission lines. Anyway, HF power is always converted to dc-voltage by means a sensor-transducer system and then measured with DVM. The simplest power meter scheme is realized with a resistive absorber dc-biased by a self-balancing loop, as Fig. 1 shows. This circuit maintains constant the absorber resistance $R(T)$ that is temperature sensitive.

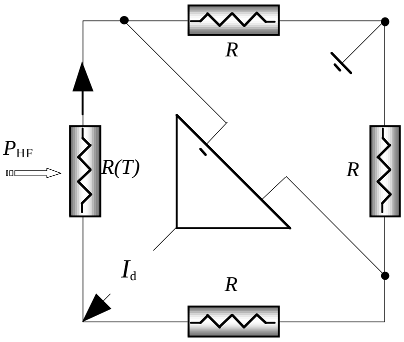

Fig. 1: Scheme of an elementary HF power meter.

When HF power enters the absorber, the self-balancing loop withdraws an equivalent dc-bias power so to counterbalance the additional temperature increase produced by the HF. The result is that to maintain constant the total power dissipated in the absorber, but by virtue of the principle of equivalence of the thermal effects, HF power is equal to the substituted dc power in the absorber [1]. Such an instrument is completely characterized by a Calibration Factor given by the following expression:

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

where η is the *effective efficiency* of the absorber, while Γ is its reflection coefficient. The parameter η has been defined as the ratio of the *dc-substituted* power to *total dissipated* power in the absorber [2]. It is measured directly with a calorimeter technique, while the reflection coefficient Γ with a Network Analyzer. Bolometric detectors are virtually free of linearity error because they work always in condition of constant power. No other parameter is therefore necessary for characterizing them.

Despite its simplicity, this instrument has technical drawbacks and is used almost only in the National Laboratories for realizing the primary power standard [3]. The reason of this specific use is that bolometer allows easily tracing the HF power to the dc current, a fundamental SI quantity. Power meter based on bolometric detection has however a limited dynamic range (-10 dBm to 10 dBm), does not well support a power overload and mainly is too sensitive at the absolute temperature.

Very soon, the bolometric instrumentation will be replaced everywhere by the more efficient one based on diodes or thermocouples [4]. Almost all modern commercial power meters are based on these sensor types that may be indifferently accepted by the same instrument mainframe. The new instrumentation is however more sophisticated than old bolometric power meters and its calibration process requires additional care. Firstly, definition (1) is not appropriate for them and also not too useful. Furthermore, the linearity of the sensor-transducer becomes an important issue and a new coefficient must be introduced for obtaining a full effective calibration of the instrument. Therefore, the calibration procedures together with the accuracy assessment must be critically revised.

2. PURPOSE

The aim of the paper is to provide technical suggestions to which performs HF calibrations, because the existing references are mainly oriented to consider the bolometric power meters, in connection with realization of the primary power standard in the National Laboratories. Seldom, the technical documentation provides enough details about the commercial instruments used by the other laboratories.

Discussion can go further if an appropriate classification of the existing instrumentation is done. We propose to group the commercial instruments in three classes A, B and C, all being fitted with diode and/or thermocouple power sensors. Bolometric power meters have been considered to introduce in the simplest manner the technique of the HF power measurement and as historical reference note. In the following, they only highlight how different may be the calibration procedure of the instruments based on diodes and thermocouples rather than resistors or thermistors, i.e. bolometers.

In the class A, we group all the power meters that are fitted with smart power sensors, i.e., sensors that are automatically and completely recognized by the instrument main frame. Basically all new products appeared on the market in the last years may be classified of type A.

In the class B, we put the instruments accepting only sensors that require some manual setting before to work properly with the main frame.

Finally, in the class C, we put all the *black boxes* for which HF power enters in and a dc-voltage is the response, proportional in a same way to the HF input. The OEM instruments belong to this class, e.g.

3. POWER METER CALIBRATION

In general, the power meter calibration consists in finding two parameters that may be considered independently. The first one is the transfer coefficient (*input power - output voltage*) of the sensor versus power level. This coefficient accounts for the sensor linearity versus power level and its determination, without signification in bolometric power meters, for what mentioned at section 1, is now mandatory for all A, B, and C instrument classes. The technical documentation does not stress on this particular. It simply addresses the linearity versus amplitude as an uncertainty issue rather then correction.

Indeed, all commercial instruments are provided with a list of calibration factors that are function only of the frequency. This is not trivial because the linearity versus power gives a huge contribution to the uncertainty budget, up to 5% and more, [3]. Anyway, we propose to define a dimensional coefficient as:

$$\alpha = \left(dc\ otuput\ voltage\right) / \left(HF\ input\ \ power\right) \qquad (2)$$

We propose also to include the values of this coefficient α in the calibration report of each power sensor instead of a typical linearity error that is only useful for the calculation of the uncertainty level of the instrument.

Measurement of α may be done for comparison with a precision step attenuator calibrated at the lowest working frequency of the power sensors. Calibrators may perform the comparison efficiently also, [4].

The second step of a power meter calibration process concerns the determination of the frequency response of the power sensor, generally named Calibration Factor K. At the state of actual art, this is known as the only calibration factor of a power sensor or power meter. The definition given by (1) for the bolometric power meters is however not very useful for all the classes A, B and C, because now the sensors *effective efficiency* η may not be in general measured directly and independently from the reflection coefficient Γ, at least by a normal operator.

At INRiM, but not only, commercial thermoelectric power sensors have been modified to be calibrated against the primary power standard, that is, to use as thermal load in the microcalorimeter. This technique allows the determination of η as in the bolometric sensor case, but the operation cannot be easily done outside the primary laboratories.

Anyway, for A and C cases, K may be most efficiently defined as:

The ratio of the power P_U *measured by the uncalibrated instrument to the power* P_S *measured by a standard when both are alternatively connected to a matched generator.*

The so defined coefficient applies as correction to the meter reading only externally, because instruments of class A and C do not generally accept updates of the internal calibration factor list, if any.

Class B power meters need another specific definition for K. The reason comes from the instrument architecture, which requires the use of 1 mW at 50 MHz reference source and the definition of a *reference calibration factor*, for performing the instrument initial adjustment, [3]. Briefly, now K is defined as [6]:

The ratio of the incident power P_{IR} *at the reference frequency to the incident power* P_{IX} *at the calibration frequency under condition that both powers produce the same sensor response, all still multiplied for the reference calibration factor* k_R:

$$K = \left(\frac{P_{IR}}{P_{IX}}\right) k_R \qquad (3)$$

Very often, this complicated definition is the reason of misunderstandings and troubles for the users.

It must be highlighted that the *reference calibration factor* k_R is a number decided primarily by the instrument manufacturer to set properly the instrument scale, even though it may be changed as convenience of the operator, anytime he performs the instrument calibration. Conventionally it has zero uncertainty and it must not be confused with the calibration factor at the reference frequency K_R, that differs in value from k_R only slightly, but is a real measured coefficient and as such affected by an uncertainty.

4. CALIBRATION METHOD AND SET-UP

The calibration of the power meters is usually done by comparison to similar instruments, but which rarely are primary standards. The most used experimental set-up is based on a resistive power splitter, whose merits and limits are illustrated in the literature [7]. The basic scheme of such a set-up is reported in the following Fig. 2.

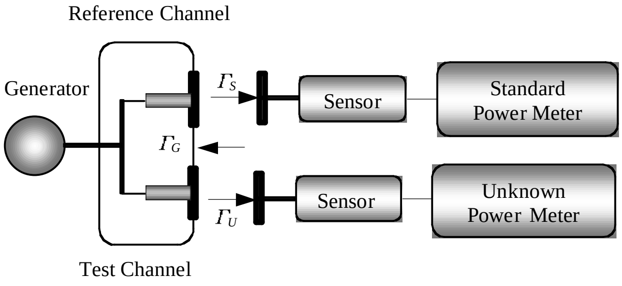

Fig. 2: Scheme of a basic calibration set-up for power meters.

Though the scheme of Fig. 2 is very popular in all laboratories because it is easy to implement and easy to run by computer, we suggest performing power meter comparisons on amplitude-leveled generators, as a better alternative. This reduces the error due to the impedance mismatches more efficiently. Figure 2 shows an example of a leveled generator obtained by means of the same power splitter.

To obtain a good impedance matching, a directional coupler should implement the T-junction instead of a resistive power splitter, because of its higher directivity and insulation between the reference and test channel. This has however a cost in term of frequency agility. Indeed, directional couplers, even of the coaxial type, are less broadband than a resistive power splitter that, e.g., may works from dc to 50 GHz.

However, it has been evaluated that the residual mismatch condition obtained both with the solution of Fig. 2 and Fig. 3 is good enough for the all the laboratories that have to produce calibration certificates, [7].

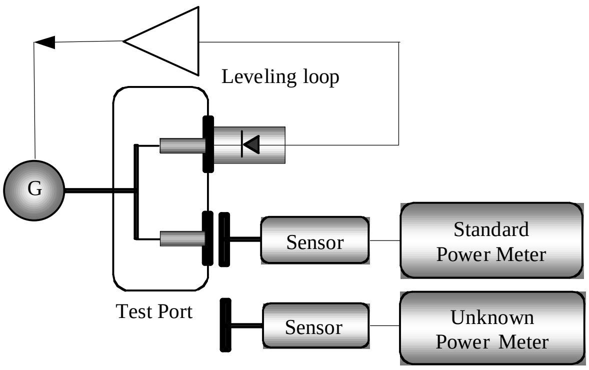

Fig. 3: Improved basic set-up for power meter comparison.

Independently by the mentioned measurement set-ups, we can write a measurement equation that applies to any type of power meter under calibration, provided to neglect the non-relevant terms, when it is appropriate:

$$K_{UX} = \left(\frac{M_{SR}}{M_{UR}}\right)\left(\frac{P_{SR}}{P_{UR}}\right)\left(\frac{M_{UX}}{M_{SX}}\right)\left(\frac{P_{UX}}{P_{SX}}\right)\left(\frac{K_{SX}}{K_{SR}}\right)k_{UR} \qquad (4)$$

The meaning of the symbols is the following:

K_{UX} *Unknown Calibration Factor at generic frequency.*
k_{UR} *Reference Calibration factor.*
K_{SX} *Standard Calibration Factor at generic frequency.*
K_{SR} *Standard Calibration Factor at reference frequency.*
P_{UX} *Measured power by Unknown at generic frequency.*
P_{UR} *Measured power by Unknown at reference frequency.*
P_{SX} *Measured power by Standard at generic frequency.*
P_{SR} *Measured power by Standard at reference frequency.*
M_{UX} *Mismatch generator–unknown at generic frequency.*
M_{UR} *Mismatch generator–unknown at reference frequency.*
M_{SX} *Mismatch generator–standard at generic frequency.*
M_{SR} *Mismatch generator–standard at reference frequency.*

Formula (4) is given assuming the readers are familiar with the basic concepts and terminology relevant to HF power transmission. They are recalled in a previous work [6], together with an explanation of (4), but some additional comment is hereby necessary.

The explicit expression of the mismatch factors is of the type $M_{LX} = \left|1 - \Gamma_L \Gamma_G\right|^2$. It depends on the complex product of the reflection coefficient of the power sensor Γ_L and the reflection coefficient of the text port Γ_G. A test port is usually referred as an equivalent generator, because never the power sensors see the real generator port. Using the scheme of Fig. 2, the operator should alternatively exchange the standard with the unknown so to compensate the asymmetry of the T-junction, at least partially. In this case for the equivalent generator Γ_G the worst value should be considered of the two output ports of the power splitter. This is however only a technical suggestion and not a mandatory step of a calibration process.

Due to the impossibility of measuring Γ_G the mismatch factors are considered only as error terms and assumed in practice equal the unit. Consequently, the knowledge of the reflection coefficient of the test ports is relevant only for the accuracy assessment of the calibration results and any self-consistent criteria of estimation may be accepted. At INRiM, e.g., it is used to evaluate Γ_G through the measured scattering parameters (S) of the T-junction, an operation that is not difficult if a vector Network Analyzer is available, [7].

Formula (4) allows an easy uncertainty evaluation of a power meter calibration, because it includes all the error sources that are relevant for the process. The total systematic uncertainty of the calibration process, or type B uncertainty, according to international metrology vocabulary [8], is obtained by applying the error propagation classic law at (4). Because this is a rational fractional formula, a very simple expression is obtained for type B uncertainty if each error term is considered a relative term. The type B total uncertainty $U_B = \Delta_{K_{UX}}$ results in the square root of a square sum:

$$\sqrt{\Delta^2 K_{SX} + \Delta^2 K_{SR} + \Delta^2 P_{UX} + \Delta^2 P_{UR} + \Delta^2 P_{SX} + \Delta^2 P_{SR} + \Delta^2 M_{UX} + \Delta^2 M_{UR} + \Delta^2 M_{SX} + \Delta^2 M_{SR}}$$

where each square term expresses an uncertainty contribution relevant to quantities previously defined. We point out that the reference calibration factor k_R does not enter in the expression of the uncertainty for the reason mentioned in section 3.

Now we want to highlight the contribution to the uncertainty of the initial setting, an operation that is requested by class B instruments. In our experience, indeed, operators find it very often difficult identifying this contribution and simply neglect it or do wrong estimation.

Provided to use the reference generator of the power meter under test for measurements at the reference frequency, the uncertainty contribution due to the initial adjusting results only related the expression:

$$\left(\frac{M_{SR}}{M_{UR}}\right)\left(\frac{P_{SR}}{P_{UR}}\right)\left(\frac{1}{K_{SR}}\right) \qquad (5)$$

where P_{SR}, P_{UR} are measured terms affected by a statistical uncertainty, K_{SR} comes with its uncertainty from a certificate and M_{SR}, M_{UR} are terms assumed equal 1 with an uncertainty of $\pm\sqrt{2}|\Gamma_L||\Gamma_G|$.

Class A instruments and in some sense also class B do not need the troublesome manual setting, before a measurement can be performed. Therefore, formula (4) reduces to:

$$K_{UX} = \left(\frac{M_{UX}}{M_{SX}}\right)\left(\frac{P_{UX}}{P_{SX}}\right)K_{SX} \qquad (6)$$

The reference frequency has no more a significant role. If a reference generator is included in the instrument, it must be considered only as a mean which to perform a functionality test with.

In the end we report the set-up scheme necessary to perform the measurement of the transfer coefficient α. Amplitude response of a power sensor may be compared against a calibrated step attenuator by inserting the last between a low frequency signal source and the power sensor, like Fig. 4 shows.

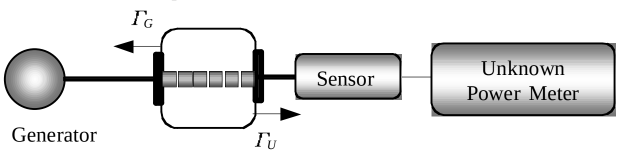

Fig. 4: Basic set up for transfer coefficient α measurement.

The system composed by signal generator and step attenuator may reduce to a dc-ac calibrator if the power sensor under calibration can accept an ac or a dc signal. Measurement accuracy depends, in this case, on the generator stability and step attenuator accuracy. Because the comparison is made at relatively low frequency, 300 kHz at maximum, mismatch contributions may be neglected, at least in a first approximation.

The concepts presented apply mainly from dc to 50 GHz, a frequency band covered by commercial coaxial power sensors. Beyond 50 GHz it is very difficult to find coaxial devices that need to be calibrated. At the state of the actual art, it is necessary still to realize waveguide power sensor for which, of course, (4) still holds.

5. CONCLUSION

Although power meter calibration seems a simple operation, authors observed that many errors appear in the comparisons and in the proficiency tests performed by accredited laboratories.

The main sources of these errors are insufficient clearness in the definition of the measurand, together with not properly right interpretations of the calibration process. The proposed power meters classification should make possible a reduction of the misunderstandings, at once with a commented calibration model that is inclusive of all the significant error terms.

We also propose to introduce a dimensional coefficient that account for the nonlinearity of the power sensors versus the power amplitude, so to be able to produce a real complete calibration of the devices. Up to now, this particular has been neglected mainly for historical reason.

The Primary Laboratories are indeed still used to realize and to maintain the HF primary power standard by means of bolometric detectors, which do not require to be characterized with such a coefficient. The evolution of the technique and instrumentation will request it, especially inside the National Laboratories.

REFERENCES

[1] A.Fantom, *Radio frequency and microwave power measurement*, Peter Peregrinus, London 1990.

[2] *IEEE Standard Application Guide for Bolometric Power Meters*, IEEE Standards 470, 1972.

[3] Hewlett-Packard Company, *Fundamentals of RF and Microwave Power Measurements*, *Application Note 64-1A*.

[4] L.Brunetti and E.Vremera, "A new microcalorimeter for measurements in 3.5-mm coaxial line", IEEE Trans. Instrum. Meas., vol. 52, No. 2, pp. 320-323, April 2003.

[6] L. Brunetti, “Accuracy assessment in HF power meter calibration”, Proc. of the 11th IMEKO TC-4 Symposium on Trends in Electrical Measurement and Instrumentation, Vol.I, pp. 233-237, Lisbon (Portugal), September 2001.

[7] L. Brunetti and E. Monticone, "Resistive power splitter in microwave power standard calibration transfer", *Measurement* Vol. 6 No. 3, Jul-Sept. 1998.

[8] *Guide to the expression of the uncertainty in measurement*, ISO, Geneva, 1995.