A New Direct Comparison Calibrator for RF Power Sensors

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Wireless products are everywhere. From wireless communications devices to children's toys to military weapons systems, more and more products are using radio frequencies (RF) (100 kHz to 1 GHz) and microwaves (1 to 110 GHz) to transmit and receive data. Wherever you find RF and microwave technology, you will most certainly find an RF power meter. Because it is impractical to measure voltage directly at these frequencies, power meters are to RF and microwave applications what a voltmeter is to DC and low frequency applications.

RF power meters use a sensor to actually detect the level of RF power. The power sensor is a device that converts RF power to DC or low-frequency power. Once the power has been converted, it can then be easily measured in terms of voltage by the power meter. The sensor is sometimes referred to as the power meter "head."

There are several types of power sensors. One of the most common types of power sensor used today for measuring power is the **thermocouple**. A thermocouple is a loop or circuit of two dissimilar metal pieces whose electrical properties are such that there is small voltage between them. As the junction of the two metals become hotter or cooler, the voltage between them changes in a predictable way. Thermocouples are more commonly used in temperature measurement applications. The principle is the same for measuring RF and microwave power: when the RF or microwave signal is applied, the energy in the signal heats the thermocouple and the RF power level is determined from the change in voltage from the thermocouple. [2]

The next most common power sensor type is the **diode detector**. This type converts AC to DC through the non-linear I-V characteristics of the diode. The useful range of diode detectors is in the -20 to -70 dBm (.01 mW to 0.1 nW) range. Therefore, most of these types of sensors are used for low power applications. However, advances in measurement techniques and diode technology have led to new diode based sensors that can be used up to +20 dBm (100 mW). [2]

The first types of sensors to be widely used to detect RF power were bolometers. "Bolometer" is a collective term that includes many devices whose resistances change as their temperature changes. As with thermocouples, when an RF or microwave signal is applied to a bolometer, the energy in the signal heats the element. The amount of RF power can be determined from the change in resistance of the bolometer. A **thermistor** is a semiconductor material with a negative temperature coefficient (resistance decreases as heat increases). Until the 1970s, thermistor-based sensors were the most widely used types. Themistors are not well suited for measuring peak power or average power in complex modulated signals. However, they measure average power of continuous wave (CW) signals very well. Their stability and repeatability make them ideal for use as lab standards.

Barretters are thin wires with a positive temperature coefficient (similar to an Resistance Temperature Detector commonly known as an RTD). This was another one of the earliest types of power sensors, and it is not used very often today. [2,3]

Thermistor-based sensors are often used as calibration standards for RF power sensor calibration. That is because they are more stable over long periods of time and more repeatable than thermocouple or diode sensors. Thermistors are less fragile than barretters and have a greater temperature coefficient. Thermistors are directly traceable to NIST; in fact NIST still uses specially constructed thermistor sensors as primary standards. Thermistors are independent of attached electronics and all measurements are made using DC devices and equipment because of the thermistor's DC substitution capabilities. [2,3]

Power Sensor Calibration

When using a power sensor, not all of the RF power applied to the sensor will be detected. The amount of power the sensor will detect is a function of frequency and it is characterized as the power sensor's **calibration factor**. Calibration factor, commonly referred to as cal factor, is simply the ratio of power detected by the sensor to the amount of RF power actually applied. The cal factor of the sensor is then used to make more accurate power measurements by compensating for the power losses in the sensor. There are two parts to the sensor's cal factor: reflected power and effective efficiency.

The reflected power of the sensor is the power that is applied to the sensor by an RF source that is not transmitted into the sensor, but reflected back to the source. This occurs because of impedance mismatches between the sensor and the source. The amount of power that a sensor will reflect back can be characterized as its reflection coefficient, or Γ (gamma). Reflection coefficient Γ is a vector quantity consisting of a magnitude ρ (rho) and phase angle ϕ (phi) and can be measured using a vector network analyzer. Voltage standing wave ratio (VSWR) is a scalar quantity and is another way to characterize the amount of power a sensor will reflect back.

Effective efficiency describes the amount of RF power actually absorbed by the detector in a power sensor. Effective efficiency describes losses in the sensor itself. RF power sensors are not 100% efficient because of internal mismatches and imperfect electrical components. Effective efficiency is the largest component of the sensor's calibration factor. Both reflected power and effective efficiency are included in the cal factor of the sensor.

The most common method for calibrating RF power sensors is the direct comparison method. The direct comparison method is "based on alternate connections of a standard and unknown power meter [sensor] to a source of rf or microwave power."[1] The source "may include a sensor-directional coupler monitor at the generator output."[1] Basically, the power of a source is measured by a NIST traceable standard and compared to the power detected from the same source by the unknown sensor. The power levels applied to both the standard and the unknown sensor are the same. Thus, the ratio of the power detected by the unknown sensor to the power measured by the standard is the cal factor of the unknown sensor.

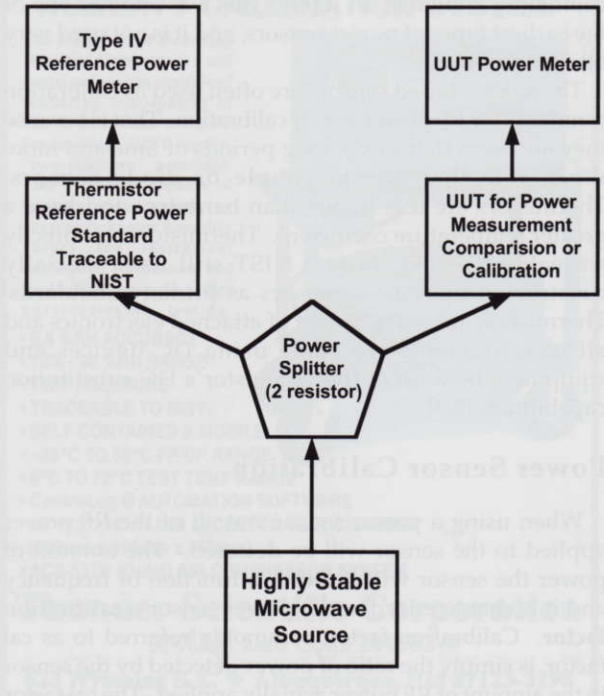

Figure 1. A direct comparison method for calibration of a RF power sensor.

Figure 2. TEGAM Model 1827 RF Power Sensor Calibrator.

Figure 1 depicts a direct comparison system using a thermistor-resistive power splitter combination as the sensor-directional coupler at the output of the source. The thermistor sensor is the standard and the power detected by the thermistor is determined by using DC substitution. Cal factor corrections for the thermistor sensor are applied to the DC substituted power to determine the actual level of RF power being applied to it. The unknown sensor or unit under test (UUT) is connected to the other output of the splitter. The power applied to the input of the splitter is divided equally between both outputs. Therefore, the cal factor of the UUT is determined by the ratio of the reading from the UUT power meter to the corrected power level measured by the standard.

A New RF Power Sensor Calibrator

The TEGAM Model 1827 RF Power Sensor Calibrator employs the direct comparison method depicted in Figure 1, but does so in a new way. Traditionally, direct comparison techniques were employed using systems that consisted of several instruments, including separate standard sensors, couplers, and power meters. The Model 1827 (Figure 2) is a single instrument that includes all of these components. The Model 1827 consists of a resistive power splitter, a temperature-controlled thermistor-based standard sensor, a DC substitution bridge, and a temperature control circuit.

The Principle of DC Substitution

The TEGAM Model 1827 uses the principle of DC substitution to measure RF power. DC substitution refers to the measurement of RF power according to the amount of DC power that must be substituted for the RF power in a bolometer in order to cause equivalent thermal effects.

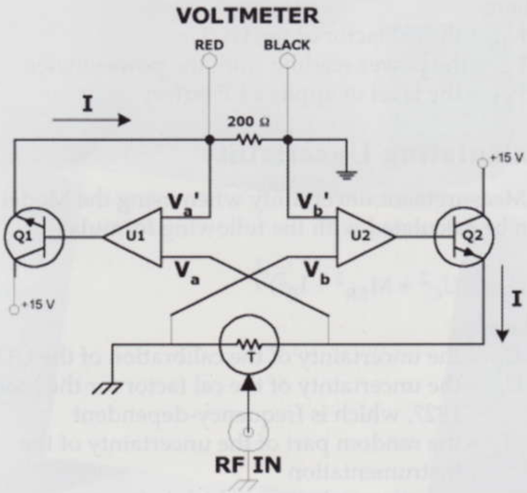

Figure 3. Simplified schematic of a Model 1827 DC substitution bridge circuit.

DC substituted power is determined by measuring DC voltages at the VOLTMETER terminals of the Model 1827.

Self-Balancing Bridge Circuits

The TEGAM Model 1827 contains a Type IV bridge circuit that performs DC substitution. The self-balancing bridge circuit, in a closed-loop configuration, consists of two legs: a precision fixed resistance leg and a leg containing a thermistor element (Figure 3). The precision resistance leg maintains a constant effective resistance value of 200 ohms.

Each leg uses an operation amplifier (U1 or U2) to sense voltage imbalances and to drive transistors (Q1 and Q2) to correct them. The power supply provides isolated ±15 volt biasing to each op-amp (U1 and U2). Since the voltage differential at the input stage of op amp U2 is negligibly small, it provides a virtual common reference to op amp U1 (i.e., it acts as a virtual common ground since the voltage approaches zero with respect to either ground). This forces the current through the thermistor to equal the current through the precision resistance leg.

The application of RF power to the thermistor element creates a decrease in the voltage drop across the thermistor element due to its negative temperature coefficient. This decreased voltage drop, in turn, creates an unbalanced bridge condition. When resistance in the thermistor element leg of the bridge changes due to the application of RF power, op amp U1 senses a voltage difference between V_a and V_a' and causes V_a' to equal V_a. When V_a' equals V_a, the voltage across the thermistor element leg equals the voltage across the precision resistance leg. Also, the closed loop circuit configuration maintains equal current throughout the bridge. Since the voltage and current throughout the circuit is equal, the resistance in both halves is also equal. Therefore, when the thermistor mount's temperature is stabilized and RF power is applied, a change in voltage across the precision resistance leg is proportional to the amount of RF power applied to the thermistor element.

Controlling Thermistor Temperature

The TEGAM Model 1827's thermistor-based sensor is a temperature-sensitive device. It is necessary to eliminate ambient temperature effects on the thermistor element in order to provide precise measurements. The temperature controller accomplishes this by raising the power standard's internal temperature to a level higher than the ambient temperature (approximately 60°C) and maintaining that level by controlling the current applied to the power standard's heater element. This prevents any thermistor imbalance due to ambient temperature change. Therefore, all temperature changes are due to the application of RF and DC power.

Making Power Measurements

The TEGAM Model 1827 measures RF power in terms of a power change across the precision resistance leg. A digital voltmeter measures the voltage across the precision resistance leg, which can be used to determine the power by the following equation:

$$P = \frac{V^2}{200}$$

where:

P = the power across the precision resistance leg
V = the voltage measured across the precision resistance leg
200 = the resistance value of the precision resistance leg

The RF power introduced to the thermistor is directly proportional to the change in DC power across the precision resistor. The change in DC power across the precision resistor leg is given by:

$$\Delta P = P_1 - P_2$$

where:

ΔP = the change in DC power across the precision resistance leg when RF power is applied to the thermistor leg
P_1 = the DC power of the precision resistance leg without RF power applied
P_2 = the DC power of the precision resistance leg with RF power applied

To determine the power across the precision resistance leg without RF power applied, measure the voltage before the application of RF power (V_1). To determine the power across the precision resistance leg with RF power applied, measure the voltage during the application of RF power (V_2). Once these two voltage measurements are made, the power can be determined by using the first equation to substitute for P_1 and P_2 from the previous formula:

$$\Delta P = \frac{(V_1)^2 - (V_2)^2}{200}$$

where:

ΔP = the change in power across the precision resistance leg when RF power is applied to the thermistor leg
V_1 = DVM reading across the precision resistor in the absence of RF power
V_2 = DVM reading across the precision resistor with RF power applied
200 = the resistance value of the precision resistance leg

Since the change in power across the precision resistor is DC power, ΔP is also represented as P_{dc}. The change in DC power across the precision resistor is directly proportional to the RF power *detected* by the thermistor. Like all RF power sensors, some of the RF power applied to the input of the Model 1827's power standard is lost by reflection and other causes before it is applied to the thermistor element. Thus, calibration factors based on frequency are associated with the Model 1827 and are applied in the following formula to determine the actual level of RF power:

$$P_{RF} = \frac{P_{dc}}{K_2}$$

where:

P_{RF} = the level of applied RF power
P_{dc} = the DC substituted power which is proportional to the RF power detected by the thermistor
K_2 = the calibration factor of Model 1827 for the applied frequency traceable to NIST

Determining the Cal Factor of the Sensor

Once the power level being applied to the unit under test (UUT) is measured by the NIST traceable standard, the sensor's calibration factor can be determined. A power reading in mW from the UUT's power meter is divided by the power level obtained from Model 1827 (P_{RF}) in mW. This ratio is the sensor's calibration factor. The calibration factor of the sensor at the applied frequency is defined by:

$$K_{1S} = \frac{P_m}{P_{RF}}$$

where:

K_{1S} = the cal factor of the UUT
P_m = the power reading from the power meter
P_{RF} = the level of applied RF power

Calculating Uncertainty

Measurement uncertainty when using the Model 1827 can be calculated with the following formula:

$$U_P = (U_C{}^2 + M_{ER}{}^2 + I_E{}^2)^{\frac{1}{2}}$$

where:

U_P = the uncertainty of the calibration of the UUT
U_C = the uncertainty of the cal factor for the Model 1827, which is frequency-dependent
I_E = the random part of the uncertainty of the instrumentation
M_{ER} = the mismatch error, which is frequency-dependent.

Model 1827 Cal Factor Uncertainty (U_C)

The uncertainty of the cal factor (U_C) refers to the uncertainty calculated for each calibration point when the Model 1827 is calibrated. It is important to note that the splitter is affixed to the thermistor standard during calibration and is not removed. Thus, the thermistor-splitter combination becomes one unit, and errors due to the splitter itself will be contained in the calibration factor of the thermistor standard.

Impedance Mismatch Error (M_{ER})

As discussed earlier in this article, impedance mismatches between two RF devices will cause some of the power applied to the sensor be reflected back to the source. Impedance mismatches between the UUT and the output of the Model 1827 are a source of errors in the UUT's calibration. The mismatch error (M_{ER}) is determined from the reflection coefficients (Γ) of both the Model 1827 and the UUT as follows:

$$M_{ER} = 1 - \frac{1}{(1 - |\Gamma_1| \times |\Gamma_2|)^2}$$

where:

M_{ER} = the residual mismatch error
Γ_1 = the reflection coefficient for the Model 1827
Γ_2 = the reflection coefficient for the UUT

Often, the magnitude is the only part of the reflection coefficient known, which will yield a "worst case" mismatch uncertainty. Sometimes the voltage standing wave ratio (VSWR) of a device is given rather than the reflection coefficient (Γ). VSWR is a scalar quantity and is related to ρ as follows:

$$\rho = \frac{S - 1}{S + 1}$$

where:

ρ = the magnitude of the reflection coefficient
S = the voltage standing wave ratio (VSWR)

Gamma Correction

If both the ρ and ϕ of the reflection coefficient are known for both the UUT and the Model 1827 (TEGAM provides this data as part of the calibration for the Model 1827), then gamma corrections can be applied to the calibration factor of the UUT. Applying gamma corrections to the calibration factor reduces the total uncertainty of the calibration by virtually eliminating M_{ER}. Gamma corrections are applied to the UUT's cal factor as follows:

$$\text{Corrected } K_{1S} = \frac{K_{1S}}{|1 + \Gamma_1\Gamma_2|^2}$$

where:

Corrected K_{1S} = cal factor of the UUT after gamma corrections are applied
K_{1S} = calibration factor of the UUT before gamma correction is applied
Γ_1 = reflection coefficient of the Model 1827
Γ_2 = reflection coefficient of the UUT

Instrumentation Uncertainty (I_E)

These uncertainties are limited by the quoted accuracies of the various equipment involved. Figure 4 shows an analysis.

Item	Specified Accuracy	Effect on Uncertainty
Model 1827		
DC Substitution Bridge Accuracy	±0.003%	±0.003
Connector Repeatability	±0.1%	±0.1
Temperature Drift	±0.05%	±0.05
Power Linearity (1 to 10 mW)	±0.1%	0 at 1mW
Calibration Factor Drift with Time	±0.5%	±0.5
Total RSS Uncertainty		±0.51%
Other Instruments		
Digital Voltmeter Accuracy	Manufacturer's specifications	
Digital Voltmeter Nonlinearity	Manufacturer's specifications	
Power Meter Accuracy	Manufacturer's specifications	

Figure 4. A Typical Instrumentation Error Analysis (I_E).

It should be noted that the Model 1827 is calibrated at 1 mW. If the calibration of the UUT is also performed at 1 mW, then the power linearity has zero effect. Otherwise, to determine power linearity, multiply the nominal power level by ±0.01% up to a nominal power level of 10 mW. From 10 to 25 mW, the additional power linearity becomes negligible.

Conclusion

The use of RF power meters and sensors has become more widespread due to the increased use of wireless products. Because RF power sensors are not ideal devices, an accurate traceable calibration of these devices is very important for getting good power measurements. Direct comparison calibration is the method of choice for calibrating sensors. Thermistor-based sensors are the standards of choice in these systems because of their stability and repeatability.

Historically, direct comparison calibrations were performed by large and sometimes costly "systems" that included several individual instruments. The new TEGAM Model 1827 RF Power Sensor Calibrator combines several of these instruments in a single instrument that is capable of calibrating sensors in the 100 kHz to 18 GHz frequency range. This economic new calibrator allows labs that previously could not justify an entire power sensor calibration system to add that capability.

The TEGAM Model 1827 is smaller, easier to use, and more cost effective than larger direct comparison power sensor calibration systems.

Acknowledgments

The author wishes to acknowledge Tracy Reindel of TEGAM, Inc. for editorial contributions to this article and Scott Andres of TEGAM, Inc. for providing technical information in support of this article.

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