A New Self-Balancing DC-Substitution RF Power Meter

NEIL T. LARSEN, MEMBER, IEEE

***Abstract*—Problems intrinsic in self-balancing Wheatstone bridges have led to the development of a new dc substitution microwave power meter. The new instrument allows four-terminal measurement of bolometer resistance and affords improved accuracy and lower noise at a lower cost than earlier instruments. Measurement errors due to imperfect behavior of the servo system are typically less than 0.01 percent.**

INTRODUCTION

FOR MANY YEARS the highest accuracy in microwave power measurements in the range from 0.1 to 10 mW has been achieved with bolometers, using dc substitution techniques. The first such precision instrument was a self-balancing Wheatstone bridge described by Engen in 1957 [1]. In 1970, we described an improved instrument which also was a self-balancing Wheatstone bridge but included a power-leveling capability and a differential voltmeter [2]. We now describe a new dc substitution power meter which provides certain advantages over the earlier instruments in lower cost, greatly simplified circuitry, improved signal-to-noise ratio in the output signal, and the reduction or elimination of certain errors.

BACKGROUND

Fig. 1 shows the form of the original self-balancing Wheatstone bridge, with a bolometer in one arm. The operational amplifier senses the error voltage across the horizontal diagonal of the bridge and drives the top of the bridge to heat the bolometer to a point which closely approximates bridge balance. The voltage across the vertical diagonal is measured before and after the RF power is applied, and the unknown RF power is related to the change in the computed dc power in the bolometer through the constants of the bolometer mount.

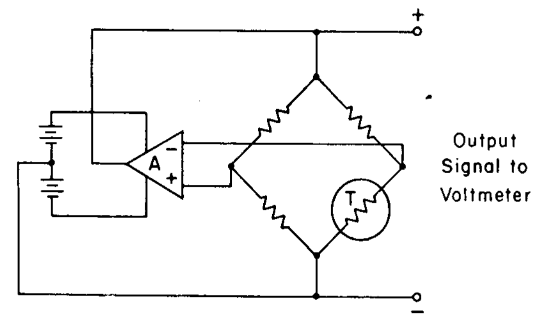

Fig. 1. Self-balancing Wheatstone bridge.

This straightforward approach is subject to certain problems, however. First, as RF power is dissipated in the bolometer, the common-mode voltage at the amplifier input changes; therefore, an amplifier having a high common-mode rejection ratio (CMRR) is required for accurate measurement. Second, the bolometer is a two-terminal device which typically must be located at some distance from the other three arms of the self-balancing bridge, since in most systems, the terminal surface of the RF portion of the system dictates the physical location of the bolometer mount. It is not common practice, nor is it usually feasible, to separate the resistances associated with the leads to the bolometer from the bolometer itself. This causes a first-order error in the measurement of the substituted power unless the actual lead resistances are measured separately, and corresponding corrections calculated for each different set of leads.

The third problem is more subtle. Consider equivalent noise-voltage generators in series with each of the input leads of the balancing amplifier. If there is no feedback from the output of the amplifier to the inverting input, then the noise will be amplified by the full open-loop gain of the amplifier and will appear at the top of the bridge—the point from which the output signal is taken. Since it is the purpose of the servo system to maintain the bridge in balance as exactly as possible, the result is a closed-loop gain for noise that is higher than the closed-loop gain for the dc signal (at those frequencies where the attenuation of the feedback path is high and the amplifier has gain). This conflict is an intrinsic problem in all systems which use a self-balancing dc bridge.

THE BASIC CIRCUIT

Active measuring circuits of various kinds incorporating operational amplifiers and isolated power supplies are not new. In 1954 Hoge [3] proposed a manually balanced circuit for the intercomparison of two four-terminal resistors. Although his system was manually operated, his concept bears some interesting similarities to the circuit described below. Others [4], [5] have reported on resistance ratio measurement techniques involving operational amplifiers. However, the prior work has dealt exclusively with linear systems involving linear resistances. In Fig. 2, an operational amplifier and associated power supply are connected with two four-terminal resistors and an external voltage source in such a way that a current I_1 flows through R_1. Under the assumption of an ideal amplifier, the current will flow as shown, and because by hypothesis no currents flow in the amplifier input leads, exactly the same current flows out of the power supply common terminal back

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The author is with the Electromagnetics Division, National Bureau of Standards, Boulder, CO 80302.

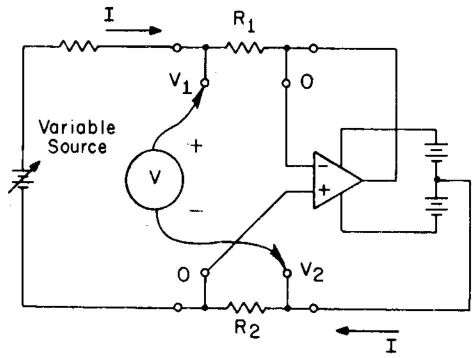

Fig. 2. A method for intercomparing two four-terminal resistors.

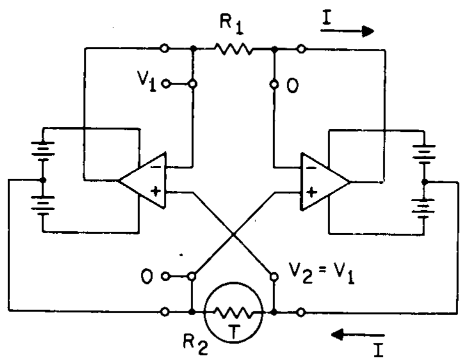

Fig. 3. A self-adjusting current loop.

through R_2 to the adjustable source. The amplifier maintains the current at such a level as to keep a zero potential difference between its input leads at all times. A voltmeter connected between the other two potential terminals of R_1 and R_2 will display a reading which is proportional to the difference in resistance between R_1 and R_2.

Now consider replacing R_2 by a negative temperature coefficient bolometer (a thermistor). If the source is varied, the current I will vary. This will cause the bolometer resistance to change and will produce a varying indication on the voltmeter. This immediately suggests closing a second feedback loop in such a way that the source voltage is controlled by the voltmeter reading to produce a voltmeter reading of zero. This concept is shown in Fig. 3, where the voltmeter and source have been replaced by a second operational amplifier and its power supplies. If a current I flows through R_1, by the previous argument, the current flowing through R_2 is identically the same. The amplifiers maintain a zero potential difference across their respective inputs by controlling these identical currents. Thus, since R_1 and R_2 have identical voltage drops across them for identical currents, R_2 must be equal to R_1. This circuit therefore forces the bolometer resistance into equality with R_1, and it does so on a four-terminal basis. This allows the elimination of the lead-error problem intrinsic to a Wheatstone bridge. The circuit has two stable states, since the current can, in principle, flow in either direction. However, once the current flow has been established, the self-balancing servo is quite stable. It is a trivial matter to provide for a predetermined direction of flow in an actual instrument.

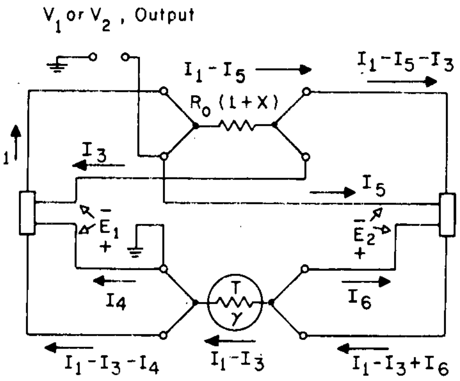

Fig. 4. Error sources in the loop. Current I_1 is the desired bolometer current.

The circuit also has interesting symmetry properties. For example, in one configuration the amplifier common-mode voltages are identically zero if the lead resistances are zero. This would allow the use of chopper-stabilized three-terminal amplifiers instead of differential amplifiers. Finally, the system works equally well with positive temperature coefficient bolometers (barretters) by interchanging the bolometer and R_1. In all, a total of eight configurations result from various combinations of amplifier configurations and bolometers.

Error Analysis

The error sources in the system due to the limitations of the operational amplifiers and the reference resistor R_1 are shown in Fig. 4. The assumptions are that the amplifier input bias currents are small but finite, that leakage currents flowing into or out of each operational amplifier and its power supplies are negligibly small, and that the amplifier input offset voltages are small but finite. The amplifier gain is assumed to be large but finite. Equation (1) summarizes the results of the analysis.

$$P = \frac{(2V_1 - V_3)V_3}{R_0} \cdot \Bigg[1 - X - \frac{E_1}{2V_1 - V_3}\left(1 - \frac{R_0^2}{\gamma V_1(V_1 - V_3)}\right) - \frac{E_2}{2V_1 - V_3}\left(1 + \frac{R_0^2}{\gamma V_1(V_1 - V_3)}\right) + \frac{R_0(I_3 - I_5)}{2V_1 - V_3}\left(1 - \frac{R_0^2}{\gamma V_1(V_1 - V_3)}\right) \pm \frac{2}{2V_1 - V_3}\left(V_1\alpha_1 + S_1\beta_1 + (V_1 - V_3)\alpha_3 + \frac{(V_1 - V_3)S_3\beta_3}{V_3}\right)\Bigg] \quad (1)$$

where

V_1 = output voltage with no RF power
V_2 = output voltage with RF power
$V_3 = V_1 - V_2$
γ = bolometer coefficient Ω/W

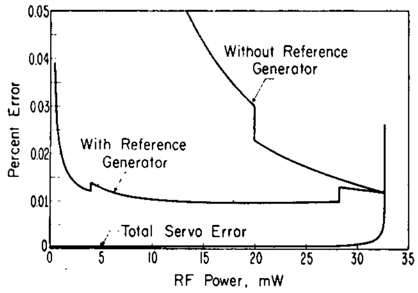

Fig. 5. Voltmeter errors with and without offsetting reference voltage generator. Total servo errors with bias currents of 6 nA and amplifier offsets of 10 μV.

S_1, S_2, S_3 = range (full scale) of the external voltmeter when measuring V_1, V_2, and V_3, respectively

$\alpha_1, \alpha_2, \alpha_3$ = fraction of reading error in the external voltmeter when measuring V_1, V_2, and V_3, respectively

$\beta_1, \beta_2, \beta_3$ = fraction of full scale error in the external voltmeter when measuring V_1, V_2, and V_3, respectively.

The remaining terms in the equation are shown in Fig. 4. Error voltages E_1 and E_2 are due to the combined effect of amplifier offset and finite gain. The loop current is I_1, and I_3 through I_6 represent the amplifier input bias currents. The nominal resistance of the reference resistor is R_0, and it may be in error by the fractional amount X. The bolometer is represented by the element T, which has an ohms-per-watt coefficient γ.

The first error term is due to the reference resistor and is not dependent on the RF power level. The second term is due to the finite amplifier gains and offsets and is a function of the RF power level. The third term is due to the amplifier input bias currents. Note that two of the four bias currents, I_4 and I_6, do not appear in the equation because they do not flow through either of the resistors in the configuration which was shown in Fig. 4. The servo errors in (1) are plotted in Fig. 5 for a typical coaxial dual-element thermistor mount with an ohms-per-watt coefficient of 13 000 and a bias current of 12.8 mA. The normal maximum RF power level for this type of mount is limited to 10 mW because of the dual-element substitution error; however, the curves have been continued to current cutoff to show the behavior of the errors. Only the power-dependent errors are shown here. The errors due to the external voltmeter are also shown in the upper two curves. If a stable variable voltage source (i.e., a "reference generator") is used to offset the voltmeter so that it is always used at as great a fraction of full-scale indication as possible, the middle curve results. If the reference generator is not used, then the voltmeter errors are magnified by using it to measure two voltages (V_1 and V_2) which are nearly the same, and then taking the difference of the squares.

We have described the errors due to the limitations of operational amplifiers and resistors. Unfortunately, the principal source of error in an actual power measurement is the limited accuracy of the external voltage measuring equipment. The errors due to the voltmeter alone are typically 20 times those due to the servo, with voltmeter specifications typical of high quality digital instruments.

Practical Realization

The unique features of the self-balancing circuitry described above make this instrument especially attractive in applications where automatic control is desired. It is often necessary to assemble several power meters in a given system, one for each of several output ports. The use of four-terminal connections to both the reference resistor and the bolometer make it possible to bring long leads from

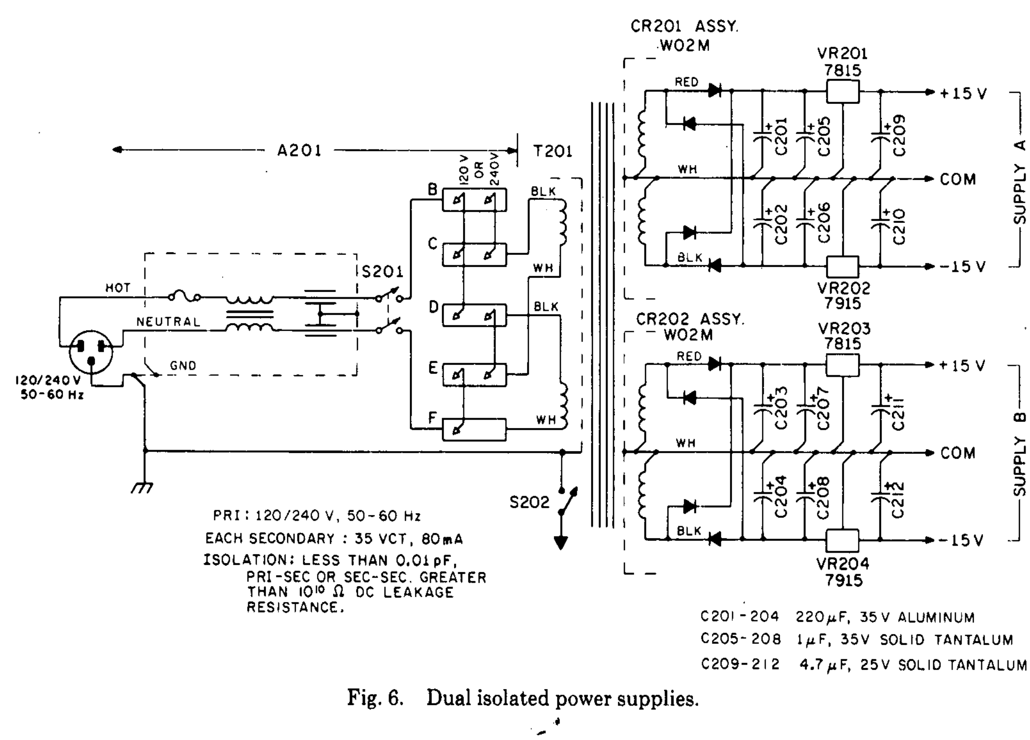

Fig. 6. Dual isolated power supplies.

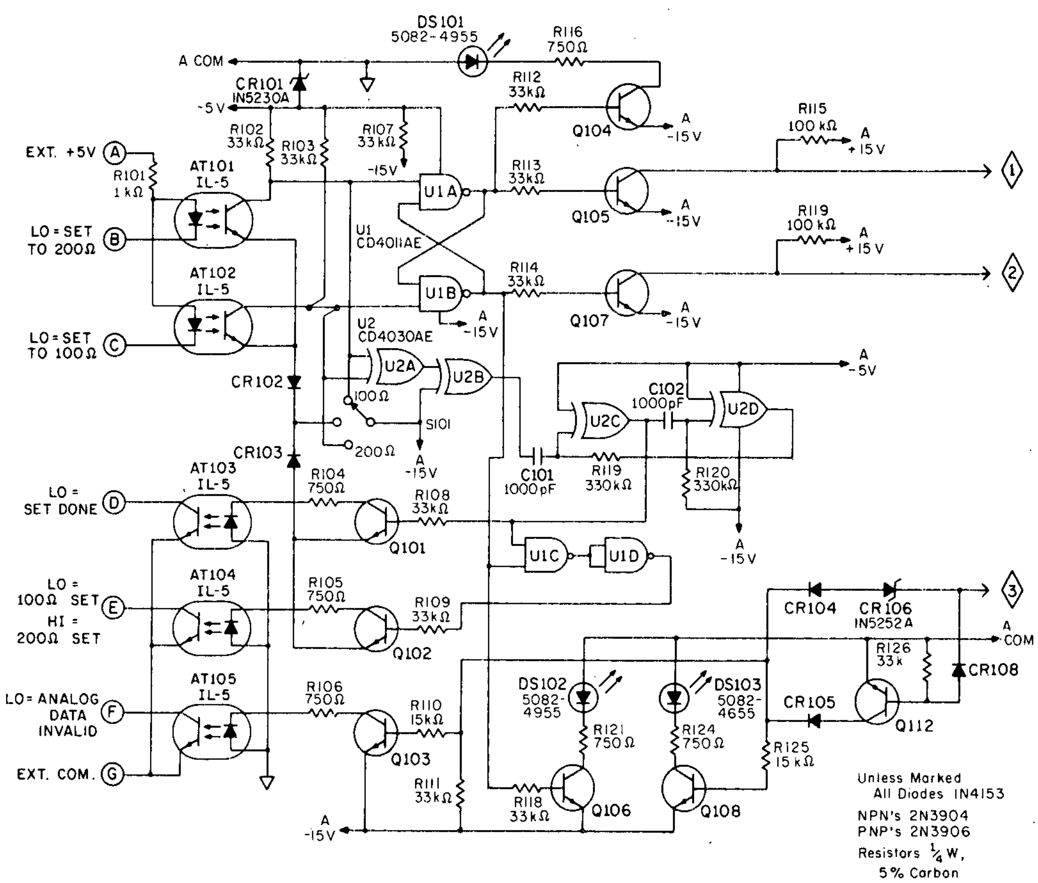

Fig. 7. Interface logic.

the bolometer units to a central instrumentation console without introducing errors. In addition, it is now possible to control the operating resistance of the bolometer unit by changing the reference resistor in response to an electrical control signal. This is much more difficult to do in a Wheatstone bridge because the contact resistance of the switches cannot be entirely removed from the bridge circuit. Now, however, it is possible to use field-effect transistor switches with no degradation in the measurement accuracy.

A complete schematic diagram is shown in Figs. 6, 7, and 8. The bulk of the circuitry is involved with the interface between the power meter and an external controller. The self-balancing portion is shown in Fig. 8. The reference resistor is comprised of R_{129} through R_{136}. It is arranged in such a way that by switching the current terminals, the effective resistance can be changed from 100 to 200 Ω. This switching is accomplished by the field-effect transistors. In addition, by removing AR101 from its socket, these resistors can be calibrated against an external four-terminal standard attached to the bolometer terminals using essentially the technique shown in Fig. 2.

The remote control inputs are applied at the left side of Fig. 7 through optical isolators. They allow an external controller to set the mount operating resistance to either 100 or 200 Ω. The mount operating resistance is determined by S101: 100 Ω, REMOTE, and 200 Ω. When in the REMOTE position, a negative-true pulse applied to terminals *B* or *C* will set the operating resistance accordingly. An elementary "hand-shake" return signal is provided at Pin *D* and a logic level confirming that the correct resistance was set appears at Pin *E*.

If the balancing servo goes out of control due to RF overload, broken or shorted lead wires, switching transients in changeover from one operating resistance to another, or a burned-out bolometer, then a front panel warning light appears, and a control signal appears between Pins *F* and *G* of the interface. This signal may be used to protect bolometer mounts against RF overload or to prevent the data acquisition portion of the system from taking invalid data.

The instrument as shown is designed to accept only negative temperature coefficient bolometers. The addition of a barretter capability requires only the incorporation of a 4PDT switch to interchange the amplifier input leads for example.

The signal output to the external voltmeter may be taken either from a terminal pair which is switched automatically as the mount operating resistance is switched, or from terminals connected directly to the reference resistor if the on-resistance of the switches cannot be tolerated. This resistance is less than 50 Ω. The Thevenin equivalent source resistance measured, for example, between terminals 2 and *E*− in Fig. 8, is very small (microohms) because of the large amount of feedback in the loop.

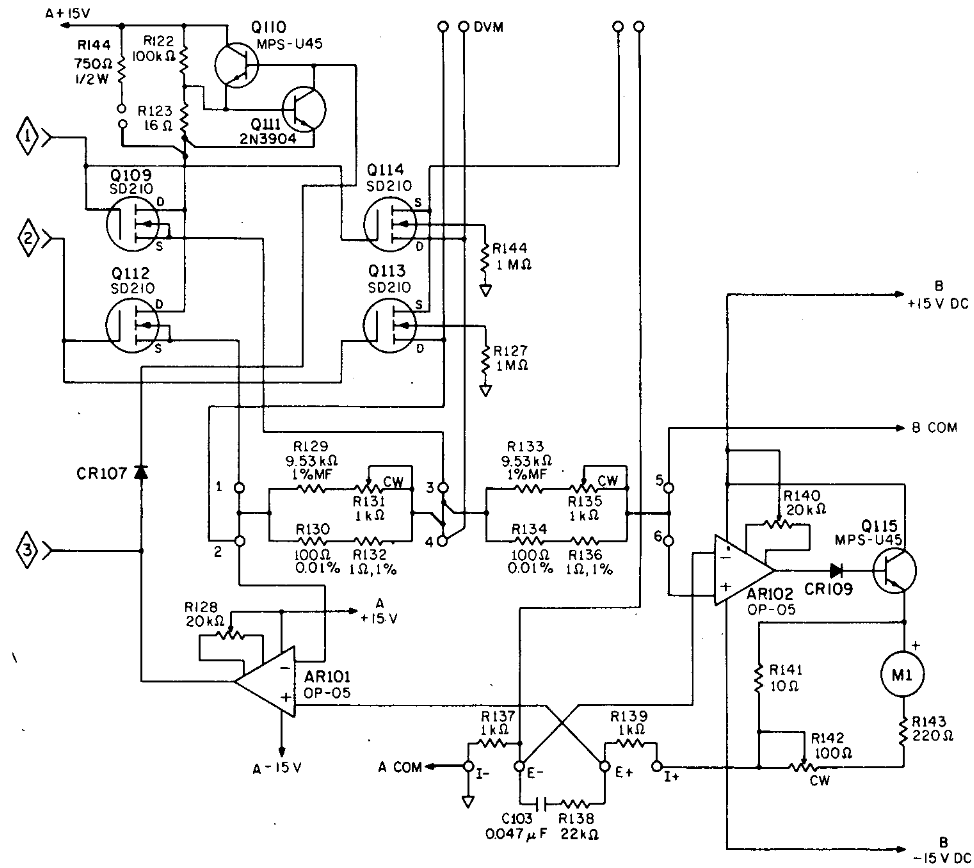

Fig. 8. Self-balancing current loop. The bolometer is connected to the terminals identified by $I-$, $E-$, $E+$, and $I+$.

PERFORMANCE

Performance of the instrument was measured in two ways. First, the magnitudes of the offset voltages and bias currents were measured under conditions of changing RF power to verify that the values used for these terms in the error analysis were realistic. Second, a system was assembled that allowed a comparison of the new instrument with an NBS Type II power meter. Mounts for the two power meters were attached to two arms of a "magic tee" or other power divider. The Type II was used to control and measure the power level from a source, while the Type IV measured the power on the other arm. The two power levels were nominally equal. The entire measurement system was under the control of a programmable calculator. Power levels were selected at random by the calculator, typically over the range of 0.1 to 15 mW, and the ratio of the bolometric powers at the two ports computed. The independence of this ratio was a measure of the precision of the two power meters and of their relative linearity. The standard deviation of a series of 1024 measurements of randomly selected levels was about 0.008 percent. The series was repeated several times for different combinations of single and dual-element mounts, with similar results. Since the two power meters were quite different internally, this is also indicative of the absolute linearity of each.

SUMMARY

We have described a new dc substitution self-balancing RF power meter which is not a form of Wheatstone bridge. Its advantages include reduced cost, lower noise, improved ease of adjustment, and adaptability to automatic control. A disadvantage is the requirement for a highly isolated power supply. The technique may also be useful with hot-wire anemometers. A patent is pending.

ACKNOWLEDGMENT

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