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Radio Frequency Power Measurements

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Roald A. Schrack

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Preface

The controlled utilization of radio-frequency power necessitates accurate methods of measurement. Although originally used solely in communications, radio-frequency power is now being widely applied in many fields, especially in medicine and industry, whenever heating not dependent on the normal methods of heat transfer is required. In navigational devices and scientific research, radio-frequency power is also finding new and extensive applications.

The increasing use of radio-frequency power underlines the need for accurate methods of measurement. Many technical considerations accentuate the difficulty of making accurate measurements, and every application of radio-frequency power requires separate investigation to ascertain the most practical measurement method.

This Circular presents a brief delineation, including theoretical background, practical limitations, and advantages of the methods currently in use.

A. V. Astin, *Director.*

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A comprehensive survey is presented of methods used to measure radio-frequency power. The methods covered are classified according to their theoretical origin. The theoretical background, practical limitations, and advantages are discussed briefly for each method. A comparative table and list of references are included.

1. Introduction

Dependable and accurate measurements of radio-frequency power are now a necessity in radio and many other fields involving electromagnetic energy. In the radio field, power measurements may be used in the determination of voltage, current, and impedance, as well as energy and efficiency. This survey is a compilation of methods that can be used in the measurement of r-f power [1 to 7].*

1.1. Accuracy and Range

Previously, power measurements made to indicate field strength and efficiency of radio transmitters rarely called for accuracies greater than 5 percent; at this time 1 percent accuracy is desirable in many cases. In this survey, accuracies between 5 and 10 percent will be termed moderate; between 5 and 2 percent, good; and better than 2 percent, excellent. One of the reasons for the low expectations in accuracy is that in the determination of power several different parameters must be measured, and the total accuracy is determined by the accuracies of the separate measurements.

Methods discussed in this survey are usable in the power range of 10^{-8} to 10^{6} w. The terminology used for the power ranges covered is 10^{-8} to 10^{-2} w, low level; 10^{-2} to 1 w, medium level; and 1 to 10^{6} w, high level. Although most methods may be adapted for use at any power level, the range of individual instruments may be limited to as low a ratio as 5 to 1.

Unless otherwise indicated, P means the average power (in watts) over 1 cycle. For complex wave shapes, the total average power is determined over a time at least as great as the period of the lowest frequency component.

The current method of dividing the radio-frequency spectrum into frequency ranges is used in this paper [8]:

less than 30 kc/s
30 to 300 kc/s
300 to 3,000 kc/s
3,000 to 30,000 kc/s
30,000 kc/s to 300 Mc/s
300 to 3,000 Mc/s
3,000 to 30,000 Mc/s
30,000 to 300,000 Mc/s.

1.2. Wave-Form and Load Considerations

The pure sinusoidal wave is representative of a discrete frequency; thus a nonsinusoidal wave represents energy being delivered at several discrete frequencies. Power measurements based on the transformation of electromagnetic energy into heat energy will respond to the total transformed energy, generally without regard to the original wave shape, which is a function of the amplitude and phase relationship of the separate frequency components.

The alternative basis of power measurement does not involve the measurement of heat, but instead the determination of electrical parameters such as voltage, current, and impedance. The basic equation is

$$P=\frac{1}{T}\int_0^T ei\,dt,$$

where P is the average power over the time interval T; e and i are the instantaneous voltage and current during that interval, respectively. For pure sinusoidal waves, this can be reduced to

$$P=VI\cos\theta, \tag{1}$$

where V and I are the rms values of the voltage and current, and θ is the phase angle between

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* Figures in brackets indicate the literature references at the end of this paper.

them. Harmonics and modulation must be removed with appropriate filtering systems when devices valid only for sinusoidal waves are to be used. In general, when nonsinusoidal wave shapes are to be measured by methods based on eq (1), extreme caution must be taken to insure that the indicated power is the sum of the powers delivered at the discrete frequencies present in the complex wave.

When the power output of a given r-f source is being measured, the type of load will determine the maximum power level at which the system can operate. Maximal transmission of power is achieved when the load impedance, seen at any point on the transmission system, is equal to the complex conjugate of the source impedance as seen from that same point. This is sometimes termed "conjugate matching." Systems having frequency-sensitive components will not, in general, deliver the maximal power at all frequencies present in a complex wave. It is necessary, therefore, when modulation products or harmonics are to be transmitted and measured without distortion, that the components of the transmission system have a bandwidth broad enough to handle the complex wave form.

Another frequently used load is the characteristic impedance (Z_0) of the coaxial line, employed to transmit the r-f power to the load. When the load matches the characteristic impedance of the transmission line, there will be no power reflected from the load, and the voltage standing wave on the coaxial line will be eliminated, lessening the danger of transmission-line breakdown due to voltage overload. This is sometimes termed "Z_0 matching."

In most cases of power measurement the actual load that will usefully employ the r-f power is not the identical load used in the power measurement. In general, the actual load and the measuring load will not have the same impedance. This change in load will effect a change in the power delivered.

The ratio of the powers delivered to two loads A and B is [1]

$$\frac{P_A}{P_B}=\left|\frac{1-\Gamma_g\Gamma_b}{1-\Gamma_g\Gamma_a}\right|^2\cdot\frac{1-|\Gamma_a|^2}{1-|\Gamma_b|^2},$$

where Γ_g, Γ_a, and Γ_b are the voltage-reflection coefficients, respectively, of the generator, and load A and load B measured at the point of connection.

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[1] This expression is derived from "Mismatch errors in microwave power measurements," by R. W. Beatty and A. C. MacPherson, which discusses the general problem of error due to mismatch (in press).

2. Calorimetry

The first law of thermodynamics, namely, the principle of the conservation of energy, forms the basis of measurement of electromagnetic energy by calorimetric methods. True calorimetric methods determine power by measurements of temperature, mass, and time [9, 10].

Those methods of power measurement which depend on known low-frequency or d-c power to reproduce the physical effect of the radio-frequency power will be termed "substitution systems" and will be covered later.

It is the aim of all calorimetric methods to dissipate completely the incoming electromagnetic energy in some medium, using the effect on the medium as a measure of the incoming power. This effect may be measured in the dissipative medium itself (direct-heating methods) or some other medium (indirect-heating methods), either of which may be static or circulating.

2.1. Static Calorimetric Systems

Static (or nonflow) systems can be quite simple in physical arrangement. The rate of temperature rise in a thermally isolated body of material of known heat capacity determines the power input into that body; the average power input over a time interval t is

$$P=MCT/t, \qquad (2)$$

where M is the mass of the thermometric body, C is the specific heat, and T is the temperature rise.[2] This equation is strictly valid only if the specific heat is a constant over the temperature range used and the thermal body is completely isolated. In practice, suitable precautions must be taken to reduce and correct for heat losses to the surrounding environment.

Static calorimetric systems can also be devised to measure power by determining the amount of the calorimetric medium undergoing change of phase, e. g., the amount of ice melted because of the energy absorbed by the ice during a certain time period [11]. The calorimetric medium will undergo no temperature change while a change of phase is taking place if all parts of the calorimetric medium are in thermal equilibrium. In this case

$$P=MH/t, \qquad (3)$$

where M is the mass of the medium undergoing change, H is the heat causing the change of phase per unit mass, and t is the time during which energy is supplied.

a. Direct-Heating Methods

The calorimetric medium is itself used to dissipate the electromagnetic energy. A portable dry-load calorimeter has been developed for use in the microwave region, which consists of a

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[2] In this formula and formulas (3) and (4), any consistent set of units may be used. If, however, the calorie is used as the unit of heat instead of the joule, the numerical constant relating the number of joules per calorie will have to be included as a multiplying factor to obtain power in watts.

coaxial line filled with a high-loss dielectric; power is measured by the rate of temperature rise in the dielectric [4]. This method can be extended to the lower frequency ranges by the use of materials that have sufficiently high loss in the frequency band desired and are capable of withstanding the temperature rise [12, 13, 14].

Water, as the calorimetric fluid and the dissipative agent, is used extensively at frequencies above 3,000 Mc/s [5, 15, 16]. As with solid dielectrics, the extension of this method to lower frequencies is dependent on the development of dielectric fluids that have sufficiently high loss in the frequency range desired.

Ammonia has been used as a dissipative medium in a power-measuring device [17, 18]. This is possible because of the inversion spectrum of ammonia at centimeter wavelengths. The extension of this method to longer wavelengths does not seem probable, since this phenomenon is extremely frequency-sensitive and absorption bands of sufficient intensity are not known to lie in the lower frequency ranges for any gas [19].

b. Indirect-Heating Methods

A resistive load immersed in a calorimetric fluid such as oil, water, or air is used in what is probably the oldest method of a-c power measurement [2, 20]. At low frequencies, load reactance can usually be made as low as desired and presents no problem if a resistive termination is desired. At radio frequencies, nonreactive loads are more difficult to obtain [21]. Matching systems are frequently necessary to adjust loads to the desired impedance. This method of power measurement is probably most suitable for medium level power measurements. For higher power levels the methods to be described next are more suitable.

2.2. Circulating Calorimetric Systems

In circulating calorimetric systems the calorimetric fluid flows at a known rate through a region where its temperature is raised by the absorption of the heat produced by the dissipation of electromagnetic energy. If the power source is capable of constant output for several minutes (or less, depending on the time constant of the device as a whole), steady state conditions can be obtained and measurements of excellent accuracy can be made. The rate at which energy is absorbed is

$$P=FCST, \tag{4}$$

where F is the volumetric flow rate of the calorimetric fluid, C is the specific heat of the calorimetric fluid, S is the specific gravity of the calorimetric fluid, and T is the temperature rise of the fluid.

Two types of circulation can be employed: the "one shot", or open, system, and the continuous, or closed, system. In the open system the calorimetric fluid is used only once [5, 22]. Open systems often employ water from the mains and thus do not require a pumping or cooling system and are more practical in some situations. The closed system, while mechanically more complicated, does not require external plumbing installations; in addition, calorimetric fluids other than water may be used [4, 5].

Because of the difficulty in obtaining and measuring a constant and accurately known rate of flow, gases are not readily usable in true calorimetric power-measuring systems. Gases may, however, be utilized as a circulating calorimetric fluid in substitution-type power-measuring systems if the effects of compressibility are taken into account.

As shown in figure 1, a temperature increment measuring device is a necessary part of a circulating system.

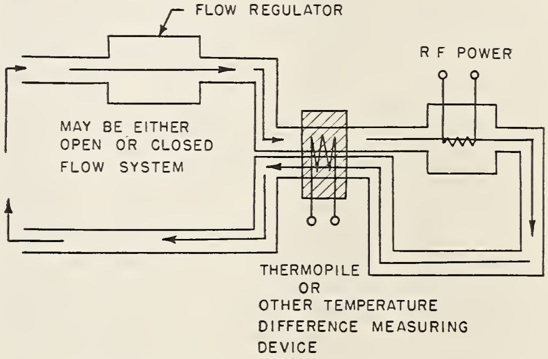

Figure 1. *Circulating calorimetric system.*

Two thermometers may be used for the temperature-difference measurement; however, thermopiles (thermels) are generally used. Thermopiles have the advantages of being temperature-difference measuring devices in themselves, having higher sensitivity and lower heat loss and time constant. In addition, the thermocouple junctions of the thermopile may be placed directly in the calorimetric fluid to obtain faster response and greater accuracy.

As in static calorimetric systems, the coolant in the circulating calorimetric system can be used both as a dissipative medium and coolant or solely as a coolant.

a. Direct-Heating Methods

In this method the circulating calorimetric medium must also serve as the dissipative medium and absorb the incident electromagnetic energy. Water, the most common calorimetric fluid, has sufficiently high losses only in the frequency region above 3,000 Mc/s, where molecular absorption takes place. At lower frequencies, a dissipative material having low resistivity might be suitable, e. g., an oil suspension of carbon particles [4]. Another difficulty in direct-heating methods is that the dielectric constant of the calorimetric fluid in the load is usually quite different from the dielectric constant of the feeder system. In order to avert the mismatch that would cause power to be reflected, some form of impedance matching is necessary. Broadband matching systems are usually employed.

b. Indirect-Heating Methods

The indirect-heating circulating coolant system is perhaps the most flexible calorimetric method of measuring power, being adaptable to all frequencies and a wide power range [23, 24, 25, 26]. The open and closed flow methods used in indirect-heating systems are identical to those used in the direct-heating systems, except that special effort must be made to effect an efficient transfer of heat from the load to the coolant. Elegant systems employing this method of power measurement have been devised and accuracies of better than 1 percent are claimed [22].

3. Substitution Methods

A large number of power-measuring devices based on the same theoretical equivalence of work and heat as the calorimetric methods do not derive their answers from calculations involving direct measurements of mass, time, and temperature. In these devices the unknown r-f power is considered to be equivalent to the known power which is substituted to cause the same temperature change in the same or similar systems. There are many systems that use this substitution method that do not measure temperature directly. They use instead some secondary effect, such as change in resistance, luminosity, or thermally produced voltage. There are two techniques for measuring by substitution that may be employed when utilizing temperature increment or some secondary effect for power measurement. The first of these techniques is that of calibration, in which at some previous time the observed physical effect is calibrated in terms of a known power input. The second is the balance technique, in which reference power from a local calibrated source of d-c or low-frequency a-c is substituted in a calorimetric body until some type of balance with the r-f power is obtained.

3.1. Adapted Calorimetry

The most direct adaption of the calorimetric method of power measurement to a substitution method is to utilize the calorimetric equipment and to fix all the parameters except one on the right-hand side in the power equation (such as eq 2, 3, 4). The variable parameter is then used as an indication of input power. In general, adapted calorimetry-type power-measuring systems may use some physical effect as a calibrated indication of power level without knowledge of the value or constancy of the other variables in the system. It is necessary only that the calibration be reproduced as a nonvariable function of the power level. The most practical basis of measurement is temperature increment.

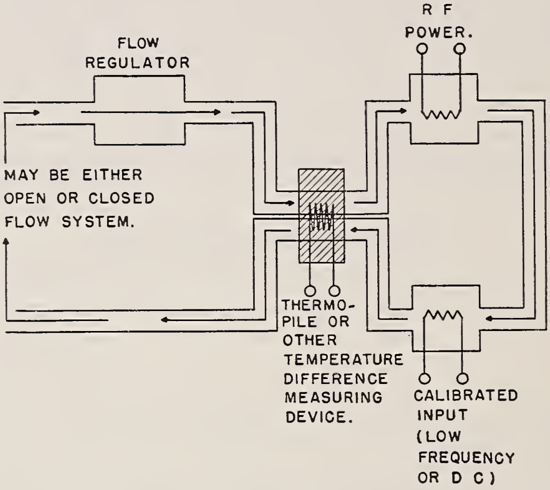

Figure 2. *Adapted calorimetric system*

Either the balance or calibration technique may be utilized to measure power by the substitution method with adapted calorimetric equipment such as that shown in figure 2. An essential modification of the original equipment is the inclusion of a heater in the flow stream. In using the balance technique, the reference power (P_1) is fed into the heater, and, after a steady state has been reached, the thermopile output is noted. The unknown r-f power (P_{rf}) is then fed in also, and the reference power is readjusted (P_2) until the previous thermopile output is obtained. The r-f power is then the difference of the two known reference powers:

$$P_{rf}=P_1-P_2. \tag{5}$$

This method is well suited to the accurate determination of incremental changes in r-f power. The upper limit of power that can be measured is determined by the initial low-frequency power (P_1).

A novel type of adapted calorimetry system of good accuracy has been developed that does not have the upper power-level limitation present in the summation system described above [27, 28, 29]. In this system a bridge using temperature-sensitive resistors is balanced at ambient temperature before power is applied to it. The r-f power and an equal amount of known low-frequency power are then applied to maintain the balance.

The balance is indicated by a null between the points *A* and *B* in figure 3.

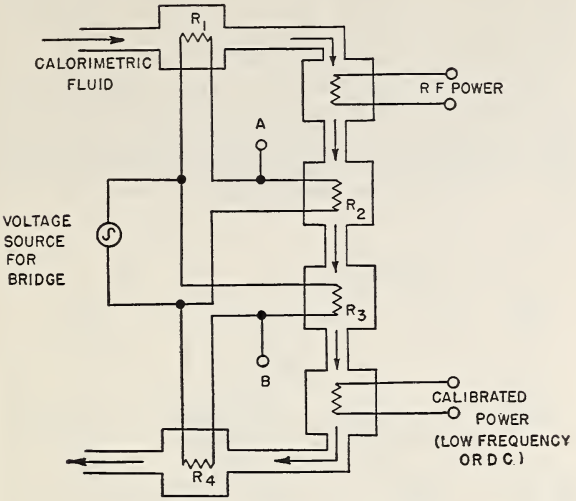

FIGURE 3. *Calorimetric bridge.*

This occurs when

$$R_1R_4=R_2R_3 \tag{6}$$

and

$$R_1=R_0, \tag{7}$$

the ambient temperature value of the resistors.

$$R_2=R_3=R_0(1+\alpha T_1), \tag{8}$$

$$R_4=R_0(1+\alpha T_2), \tag{9}$$

where α is the temperature coefficient of the resistors, T_1 is the temperature rise due to the absorption of r-f power, and T_2 is the temperature rise due to the absorption of the known power and r-f power. Substituting eq (7), (8), and (9) in (6), we obtain

$$R_0^2(1+\alpha T_2)=R_0^2(1+\alpha T_1)^2. \tag{10}$$

Then, to a close approximation,

$$T_2=2T_1. \tag{11}$$

The temperature rise due to the r-f power is therefore equal to the temperature rise due to the calibrated input. Since the calorimetric body is the same for both sections of the system, equal temperature rise implies equal power input, thus

$$P_{rf}=P_{dc}. \tag{12}$$

The device shown in figure 4 is currently being used for power measurements at the milliwatt level in the frequency region above 300 Mc/s; its extension to any power and frequency range is entirely feasible. Power maintained at a constant level is fed into one of the calorimetric bodies; the other is used as a reference point.

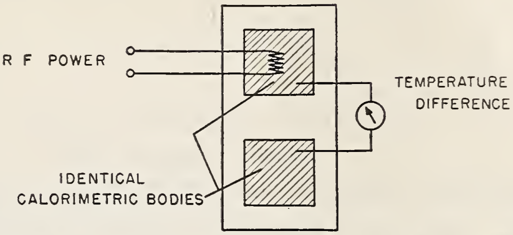

FIGURE 4. *Substitution system with calorimetric reference.*

The temperature difference between the bodies is then, with simplifying assumptions

$$T=PR\ (1-e^{-t/RC}), \tag{13}$$

where *P* is the power input level, *R* is the thermal resistance to the surroundings, *C* is the heat capacity of the calorimetric bodies, and *t* is the elapsed time. Experimental determinations of *R* and *C* are made with d-c power; this information is then used to determine r-f power levels. A precision of better than 1 percent has been obtained in cross checks with bolometric methods [30].

The advantage of this symmetrical system is that even though the temperature rises be quite small (as in microcalorimetry work), excellent accuracies can be obtained because the effect of ambient-temperature variations will be cancelled out. If the *R* term in eq (13) is the same for d-c and r-f heating, a specific equilibrium temperature will be equivalent to a specific power input. This relationship, once determined for conveniently measured d-c power levels, can then be easily applied to r-f power measurements.

Devices simpler in physical construction than figure 4 and having no calorimetric reference have

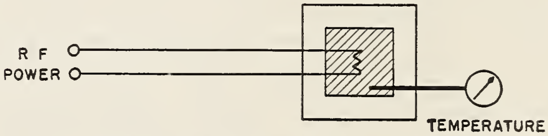

FIGURE 5. *Generalized substitution system.*

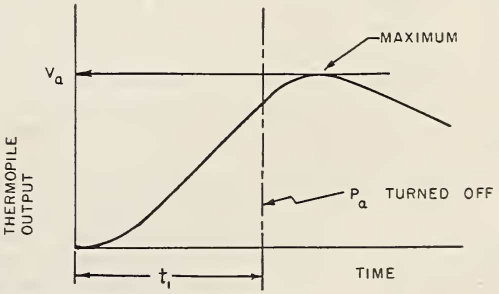

FIGURE 6. *Thermopile output versus time.*

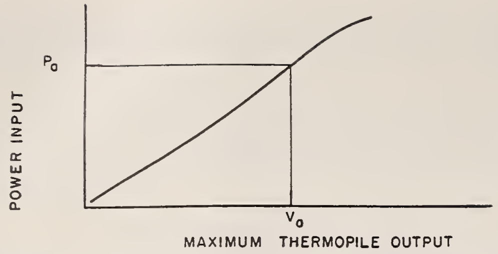

Figure 7. *Thermopile output versus input power level.*

been developed. Also based on eq (13), they, too, show high accuracy. One method is to calibrate a device, such as shown in figure 5, for different known power levels. At each level (P_a) the power is fed into the load for a fixed period of time (t_1) that is used for all measurements. The maximum thermopile output (V_a) is noted, as in figure 6; this information is then plotted, as in figure 7, and used for the determination of r-f power levels.

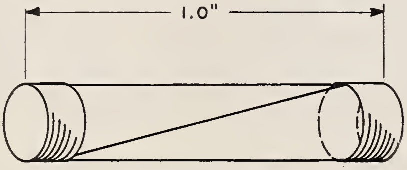

Figure 8. *Barretter.*

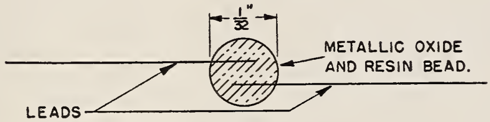

Figure 9. *Thermistor.*

3.2. Bolometers

The bolometer is a small temperature-sensitive resistive element used to measure low- and medium-level power. The heating effect of the dissipated r-f power results in a change of its resistance. The bolometer is generally incorporated into a bridge network, so that a small change in resistance in the bolometer will be easily detected and measured [31, 32]. Figures 8 and 9 illustrate two types of bolometers [33]. The barretter is a very fine wire, about 10^{-5} in. in diameter, usually platinum, which has a positive temperature coefficient, short time constant, and limited range, and is easily destroyed by overloads [34]. Gas-filled barretters have been developed in which the maximum power level has been increased from 500 mw to 20 w because of the more efficient heat dissipation [6, 35].

The thermistor bead is a semiconductor bolometer element with a negative temperature coefficient [36]. It is usually composed of manganese and nickel oxides in a resin binder and can be made physically more compact than the barretter and be designed to operate at the characteristic impedance of a transmission line. The thermistor is also characterized by moderate time constant, superior mechanical and electrical ruggedness, and greater sensitivity than the barretter. Figure 10 compares the electrical characteristics of the barretter and the thermistor.

Attention must be paid to the design of the bolometer mount, for very often the frequency characteristics of the bolometer system are due more to the mount design than to the characteristics of the bolometer itself [37].

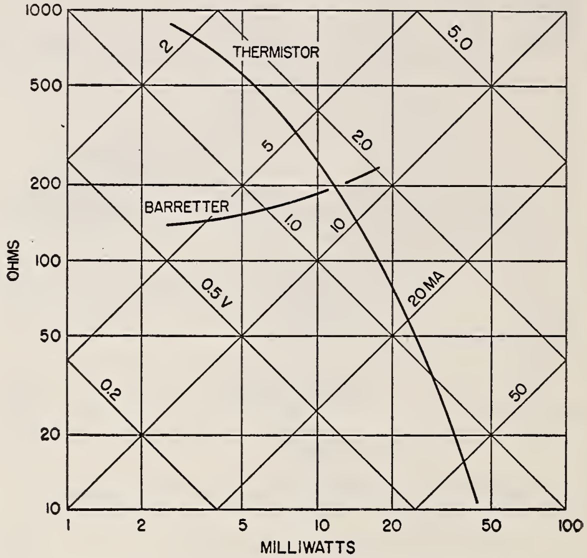

Figure 10. *Typical bolometer characteristics.*

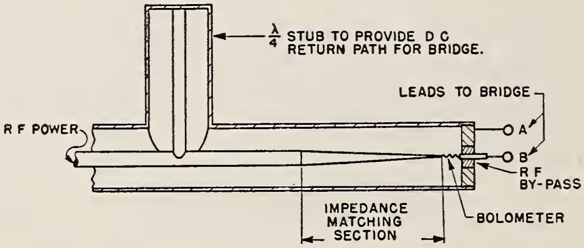

Figure 11. *Impedance-matching bolometer mount.*

Broadband-impedance-matching devices, such as the taper shown in figure 11, are commonly employed to match the bolometer to the transmission line when the bolometer is not operated at the characteristic impedance of the transmission line. Taper systems are adequate matching devices where impedance magnitude change is desired and no reactance shift is necessary. This is usually the case for the thermistor.

Because of the length of the conventional wire barretter, it may be more difficult to match, and under some circumstances, where the wavelength is commensurate with barretter length, erroneous measurements may result from uneven heating of the barretter [38, 39].

Bolometers may be used in the bridge circuit shown in figure 12 in two different ways, as a balanced bridge or as an unbalanced bridge [40, 41, 42, 43]. In the balanced-bridge system known power is substituted, at the time of measurement, for the unknown r-f power that is to be measured. The operation of the unbalanced bridge is based on the same principle as the calibrated substitution systems described before, in that the unbalance current of the bridge is, at some previous time, calibrated in terms of a known power.

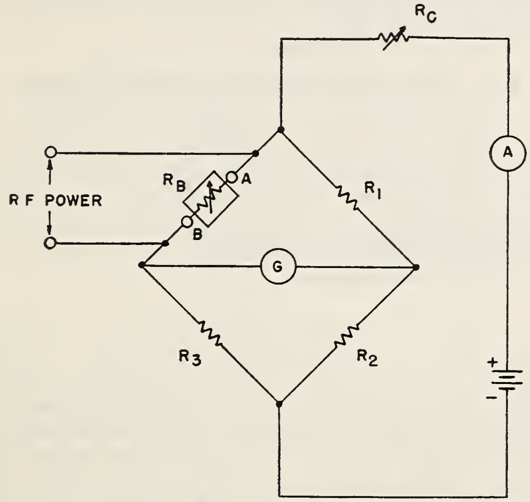

Figure 12. *Basic bolometer-bridge circuit.*

a. Balanced Bridge Theory

For simplicity, let us assume that in figure 12

$$R_1=R_2=R_3. \tag{14}$$

Then the bridge will balance when

$$R_b=R_1=R_2=R_3, \tag{15}$$

where R_b is the resistance of the bolometer. To enable the bridge to operate correctly, R_1 is chosen in accordance with the operating characteristics of the bolometer and the impedance-matching device used to match the bolometer load to the transmission line.

The initial balance of the bridge is performed with no r-f applied. The total power dissipated in the bolometer is then

$$P_1=\frac{1}{4}I_1^2R_b. \tag{16}$$

The r-f power to be measured is then applied, and R_c is readjusted to regain balance. The d-c power dissipated in the bolometer is

$$P_2=\frac{1}{4}I_2^2R_b. \tag{17}$$

The total power dissipated in the bolometer muss be the same as before because the bridge it balanced, thus

$$P_1=P_2+P_{rf} \tag{18}$$

or

$$P_{rf}=\frac{1}{4}(I_1^2-I_2^2)R_1. \tag{19}$$

Many elegant methods have been designed to make this determination easier, but all utilize the same basic idea [44, 45, 46, 47].

Bolometers, when used in balanced-bridge circuits, offer high-accuracy methods of measuring r-f power at all frequencies. The power range of individual units may be quite limited, but bolometers offer the most sensitive method of power measurement, usable down to 10^{-7} w and up to 1 w. The limitations of noninstantaneous reading and limited power range do not keep the balanced-bridge bolometer from being a popular method of measurement for low-level r-f power.

b. Unbalanced Bridges

The direct-reading method of the unbalanced bridge is faster in operation than the balanced bridge and can more accurately read low power levels where its linearity is good and where it may be difficult to read I_1 and I_2 of eq (19) with sufficient precision. A drawback of the unbalanced-bridge system is that its calibration is for only one ambient temperature. Provision must be made for this fact because small variations in temperature greatly affect the characteristics of the bolometer. The most fundamental approach to this problem is to place the bolometer element in a temperature-controlled housing designed to keep the temperature constant. This method was employed in the earliest instruments using barretters as bolometer elements. With the introduction of thermistors, another approach was used; thermistors made to be sensitive to ambient-temperature variations were placed in compensating circuits [4, 48]. Constant sensitivity, which is a necessity if the calibration is to have any value, has been achieved to within ½ decibel over a 75-deg C temperature change. Balance stability is not so important, as it is usually possible to rebalance the bridge before making readings.

Several unique bolometer elements have been developed that do not fall into the previously covered categories [38, 49]. A metalized glass-tube bolometer designed for use in coaxial mounts has been developed; it has good overload characteristics, stable calibration, and sufficient sensitivity for medium-level power measurements. An additional advantage of this type of bolometer is that both the diameter and the specific resistance of the element are controllable; by properly varying these parameters, extremely broadband equipment can be realized [4].

Another type of bolometer, shown in figure 13, consists of a thin tellurium-zinc film, having a conductivity of 500 mho/m, placed as a short section of high-loss line to dissipate one-half of 1 percent or less of the power being transmitted [50]. The change in resistance of the film, caused by the temperature rise, is measured in an external bridge connected to the points *A* and *B*. The device has proved to be of moderate accuracy at low power levels from 1,000 to 10,000 Mc/s. The principle can be applied at low frequencies, but the device has the limitation of being equally sensitive to transmitted and reflected power and can, therefore, be used to indicate transmitted power only on lines with unity standing-wave ratio.

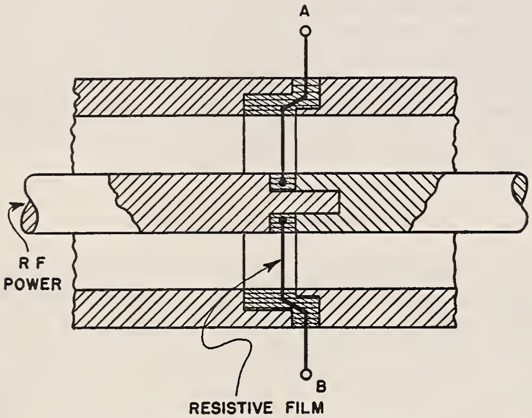

Figure 13. *Broadband bolometer.*

3.3. Photometric Systems

When sufficient power is dissipated in a resistance element to cause emission of visible radiation, the power level may be correlated with the intensity or color of that radiation [51, 52, 53]. Photoelectric cells may be used in photometric systems employing either the calibration or the balance system of measurement; figure 14 shows a device utilizing a photoelectric cell to indicate the intensity of emitted radiation. The cell current is calibrated in terms of known power dissipated in the resistive element [54, 55]. Another method utilizes special lamps, which have been designed for power measurement, having two filaments of identical characteristics in the same envelope [56]. Radio-frequency power is fed into one filament, and the calibrated d-c power fed into the other filament is adjusted until the two filaments are of equal brilliance. The unknown r-f power is then assumed to be equal to the calibrated power. Errors as low as 5 percent are claimed for measurements made by visual comparison. The main advantage of the photometric system is that relatively high powers (up to 20 w) can be measured quickly with moderate accuracy. Because of their size and impedance characteristics, the lamps must usually be used with impedance-matching equipment.

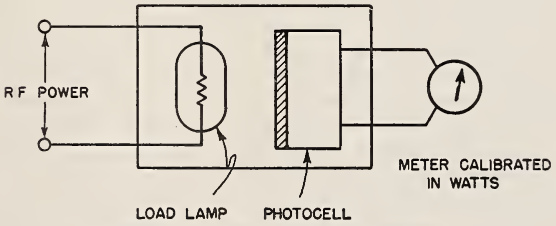

Figure 14. *Photometric wattmeter.*

3.4. Temperature-Limited Diodes

At frequencies where lead lengths are not a deterrent, conventional diodes under temperature-limited operation offer an extremely sensitive method of power measurement [3, 57]. The anode current of a temperature-limited diode is given by Richardson's equation

$$I_s = AT^2\epsilon^{-\frac{W}{KT}} \tag{20}$$

where I_s is the anode current, T is the emitter temperature, and A, W, K are physical constants. I_s is very sensitive to T because of the exponential factor. When the power level is sufficiently high to provide anode current of the order of milliamperes, extremely simple and precise calibration-type devices, such as shown in figure 15, can be used. Because of the exponential relationship of anode current to input power, results of excellent accuracy can be obtained where this device is incorporated in a balance-type system. A commercial unit of this type is available, using a miniature tube as a temperature-limited diode in a substitution balance circuit controlled by a feedback system that keeps the total plate current constant. An over-all accuracy of 2 percent for medium power levels is claimed for frequencies up to 300 Mc/s with this instrument [58].

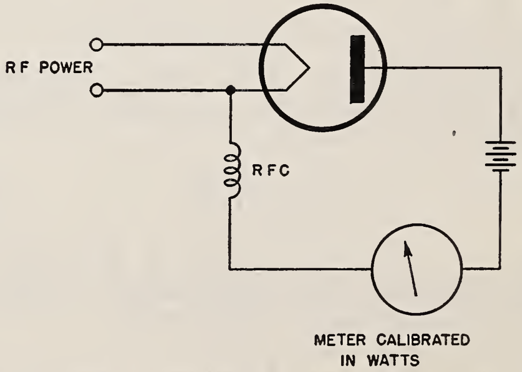

Figure 15. *Temperature-limited diode wattmeter.*

3.5. Thermocouples

The measurement of the thermal emf generated by the thermocouples is probably the most widely used method of determining the temperature rise caused by the dissipation of r-f power. The combination of a thermocouple and a resistive element in which the r-f power is dissipated is termed a "thermoelement" and is well adapted to most measurements because of the isolation of the r-f power from the d-c measuring circuit, as shown in figure 16. Thermoelements with "straight-thru" heaters have been developed which are available commercially in a number of sizes that cover a power range from 1 to 150 mw and are usable up to 300 Mc/s. Experimental thermoelements have been developed that operate at power levels up to 50 w for frequencies below 300 Mc/s.

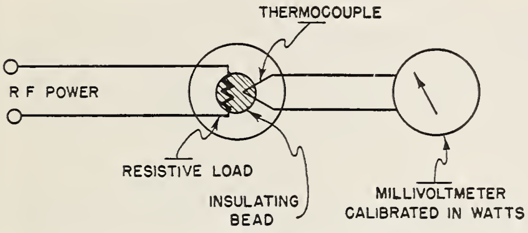

Figure 16. *Thermoelement wattmeter.*

Several high-resistance thermocouple-type units have been developed and are shown in figure 17 [4]. In these units the r-f load is placed between the thermocouple junctions; this is done to raise the resistance of the unit so it will be easier to match impedances. In type *A* of figure 17 a carbon unit separates the thermocouple junction, whereas in type *B* a thin metallic film on a glass bead forms a resistive load that has the advantage of decreased variation of resistance due to skin effect.

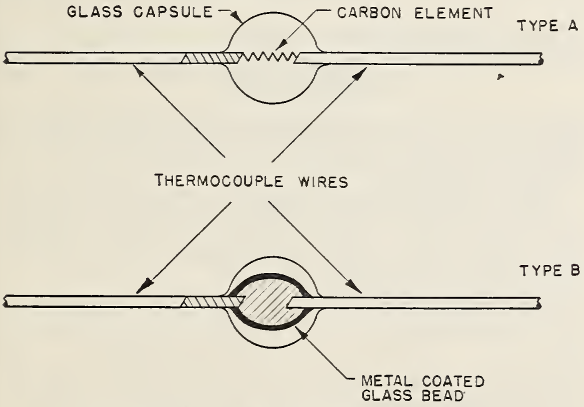

Figure 17. *Direct-heating thermocouples.*

In thermocouple devices sensitivity is generally less than a millivolt output per milliwatt input. If, however, the units are operated in a vacuum, efficiency is raised, and the output is increased several hundred percent by decreasing the heat lost by convection and conduction.

Thermocouples can also be used in power-measuring systems that measure the heat radiated from some power-dissipating device. A good qualitative indication of the power generated by a vacuum tube may be achieved through the use of a thermopile radiation monitor [60]. A thermopile is placed in a directional metallic reflector so that the output of the device will be sensitive to heat radiated from a particular area. A vacuum tube is placed to occupy the area of sensitivity of the device; a constant sample of the radiant energy from the tube is then an indication of the total power dissipated by the tube.

When the vacuum tube is not acting as an r-f generator the total d-c input power must be dissipated in heat:

$$P_{dc}=V_pI_p=P_h \text{ (dissipated heat).} \qquad (21)$$

The thermopile current, I_t, will be a function of this dissipated power, P_h. A graph of this relationship may be obtained by operating the tube at different levels of d-c power input.

The vacuum tube is then operated as an r-f generator; the amount of power dissipated as heat is determined from the thermopile current, and the r-f power generated by the tube is

$$P_{rf}=P_{dc}-P_h. \qquad (22)$$

Equation (22) holds strictly for oscillators and class *A* amplifiers. In class *B* and class *C* amplifiers the r-f input power must be taken into account. Although adaptable to any power level and frequency, this method indicates only the r-f power generated; at high frequencies a considerable fraction of the r-f power may not be available for use because of losses and poor matching.

4. Single-Variable Devices

The methods of power measurement covered thus far are dependent on the transformation of electromagnetic energy into heat. The action of all the subsequent measuring devices will depend on measurements of voltages or currents. For a pure sinusoidal wave

$$P=I^2R \qquad (23)$$

or

$$P=V^2G, \qquad (24)$$

where I is the rms current, V the rms voltage, R the resistance through which the current flows, and G the conductance across which the voltage appears. Equations (23) and (24) can be used with nonsinusoidal wave shapes, provided R (or G) is independent of frequency and that the measured I (or V) is rms.

Electronic squaring devices such as the full-wave square-law detector and the newly developed square-law tube [61], as well as hot-wire and thermocouple-type instruments satisfy this latter condition. The diode detector, except under special conditions, and other peak-reading instruments do not satisfy this condition and are, therefore, not suitable for making power measurements involving complex wave shapes.

4.1. Current-Measuring Systems

If a lossless transmission line is terminated in its characteristic impedance, which is purely resistive, the power delivered to the load may be determined from

$$P=I^2R_0, \tag{25}$$

where I is the rms current, and R_0 is the characteristic impedance of the line. Several wattmeters based on this relationship assume a flat line (no standing wave) and measure current at a point distant from the load [5, 62, 63]. The current-measuring system illustrated in figure 18 must be used with a source of r-f power that has low d-c resistance to provide a return path for the direct current generated by the thermocouple that serves as its own heater. The components L_f and C_f are inserted to isolate the d-c galvanometer circuit from the r-f circuit. The use of thermoelement units having isolated heaters eliminates the need for the d-c return path. Good accuracy at medium- and high-power levels up to microwave frequencies can be expected from devices of this nature.

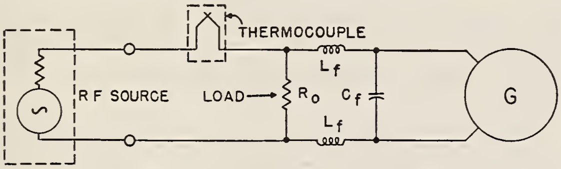

FIGURE 18. *Thermocouple wattmeter.*

4.2. Voltage-Measuring Systems

Power measurements based on eq (24) can be made with loads that match the transmission line, using the relationship

$$P=\frac{V^2}{R_0}, \tag{26}$$

where R_0 is the characteristic impedance of the transmission line, and V is the rms voltage. Numerous commercially available instruments utilize this relationship, and devices have been built covering the power range of 20 mw to several thousand watts for frequencies up to 10,000 Mc/s [4, 50, 64, 65].

Power measurements can also be made based on eq (24), using a recently developed admittance bridge to measure G [66]. The voltage and conductance must both be measured at the same point to determine the transmitted power. This device can thus be used in conjunction with a voltmeter to monitor power with moderate accuracy from 1 to 300 Mc/s and for power levels down to 20 mw. One severe limitation of the device is that approximately one-half the incident power is dissipated internally; this limits the high-power level.

4.3. Slotted Transmission Lines

When the power supplied to a load that is not matched to the line is to be measured, the voltage distribution along the transmission line must be known. This voltage distribution can be determined if the voltage standing-wave ratio and the voltage at some accessible point on the line are known. The load is generally used as the point of voltage measurement. For a lossless transmission line the voltage distribution can be expressed in the form

$$V_x=V_{\max}[\cos \beta x+(j/\rho) \sin \beta x], \tag{27}$$

where $V_{\max}$ is the rms voltage at a point of voltage maximum on the line, and x is the distance from that point; ρ is the voltage standing wave ratio (cf eq (37)), and $\beta=2\pi/\lambda$.

The power delivered to a load by a transmission line of impedance Z_0 is

$$P=(V_{\max})^2/\rho Z_0 \tag{28}$$

From (27) and (28) we obtain

$$P=(V_L)^2/\rho Z_0[1+(1/\rho^2-1)\sin^2 \beta y], \tag{29}$$

where V_L is the rms voltage at the load, and y is the distance from the load to the nearest point of voltage maximum.

The determination of power is, in this method, dependent on the determination of ρ by the use of a calibrated probe to examine the voltage distribution on the slotted line.

The method now to be described is superior to the preceding one in that it is not necessary to know the probe-detector characteristics. The equipment must, however, be of such a nature that the load on the line can be replaced by a short, and input power to the line be easily adjusted.

In the initial step the unknown power is delivered to the load as shown in figure 19, and the deflections of the probe meter at the point of maximum deflection ($D_{\max}$), at the minimum ($D_{\min}$), and at the load or a half wavelength away (D_L) are noted, as well as the load voltage, V_L. The input power to the line is then reduced and the line shorted. The input power is adjusted so that the maximum deflection of the probe meter ($D_{\max}$) is the same as it was in the initial step. The distances ΔS_1 and ΔS_2, as shown in figure 20,

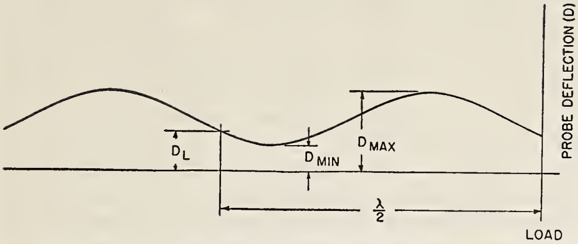

FIGURE 19. *Voltage standing wave on loaded line.*

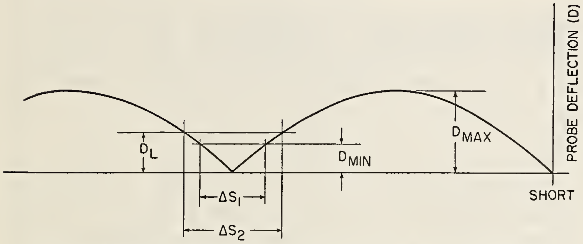

FIGURE 20. *Voltage standing wave on shorted line.*

are now determined; they are the separation of points on either side of a minimum, where the probe-meter deflections are, respectively, $D_{\min}$ and D_L. Because the voltage distribution on a shorted lossless transmission line is that of a full-wave rectified sine wave, we can write

$$\rho=1/\sin(\beta\Delta S_1/2) \qquad (30)$$

and

$$V_{\max}=V_L/\sin(\beta\Delta S_2/2). \qquad (31)$$

Substituting eq (30) and (31) in eq (28), we obtain, for the power delivered to the load

$$P=\frac{(V_L)^2\sin(\beta\Delta S_1/2)}{Z_0\sin^2(\beta\Delta S_2/2)}. \qquad (32)$$

By using these methods and their modifications, power can be measured with excellent accuracy in the frequency range in which slotted lines are practicable [67, 68, 69].

A fixed frequency adaptation of slotted-line technique using three voltmeters spaced λ/8 apart along the line has been developed and used for frequencies up to 3,000 Mc/s. The power transmitted by the line is

$$P=\frac{V_1V_3}{R_0}\sqrt{1-\frac{1}{4}\left(\frac{2V_2^2-V_1^2-V_3^2}{V_1V_3}\right)^2}, \qquad (33)$$

where V_1, V_2, and V_3 are the rms voltages on successive meters along the line [70].

5. Two-Variable Devices

Power-measuring devices in which both voltage and current are determined parameters will be termed "two-variable devices." Their operation is based on eq (1).

5.1. Electromagnetic and Electrostatic Wattmeters

The electrodynamic wattmeter, commonly used for measuring power at frequencies up to about 800 c/s, utilizes electromagnetic forces [71]. A modified quadrant electrometer can be used to measure power. Its operation is based on the use of electrostatic forces [1]. Accuracies as high as one tenth of 1 percent are claimed for these devices when operated within their frequency range. Unfortunately, the frequency range is low because of the phase-shifting action of distributed reactances at higher frequencies. Electrodynamic wattmeters have been utilized as indicating devices, however, in r-f power-measuring systems [72].

5.2. Thermal Wattmeters

Several devices utilize square-law elements to determine power by means of the relationship

$$AB\cos\theta=\tfrac{1}{4}[(\boldsymbol{A}+\boldsymbol{B})^2-(\boldsymbol{A}-\boldsymbol{B})^2]. \qquad (34)$$

Devices whose operation is based on this relationship are termed quadratic "multipliers." The emf developed by a thermoelement is proportional to the square of the input current (or voltage) and

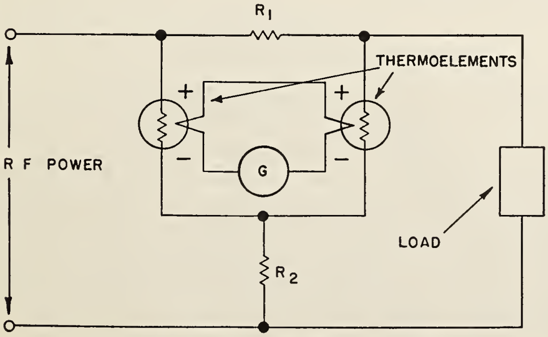

FIGURE 21. *Resistive thermal wattmeter.*

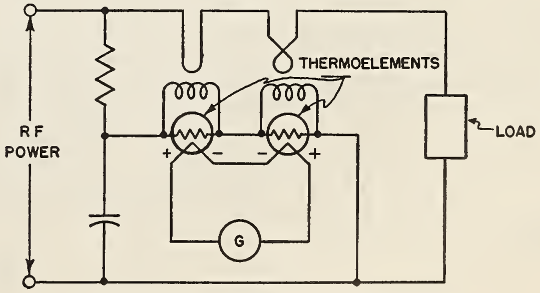

FIGURE 22. *Reactive thermal wattmeter.*

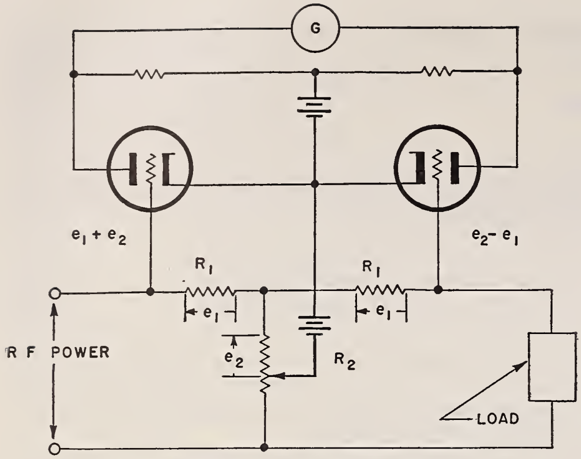

Figure 23. *Vacuum-tube wattmeter.*

can, therefore, be used in these devices. The thermal wattmeter of figure 21 utilizes eq (34) to a close approximation and thus yields power measurements of moderate accuracy when the power factor is high [71]. Figure 22 illustrates a modification of the circuit of figure 21, using reactive components for measuring power at kilowatt levels for frequencies up to 2 Mc/s [73].

5.3. Vacuum-Tube Wattmeters

The d-c component of the output of vacuum tubes operated as square-law detectors is proportional to the square of the a-c input voltage. Tubes operating under these conditions, as shown in figure 23, can be used to effect a more sensitive power-measuring device than the thermal wattmeter [74, 75, 76]. A well designed wattmeter of this nature should provide good accuracy in the medium-power-level range. The frequency limit due to tubes would be about 50 Mc/s with presently developed tubes.

Several electronic multiplying circuits utilizing the characteristics of multigrid tubes have been developed for use as wattmeters, but instability and frequency limitations have thus far prevented the exploitation of these devices in the high-frequency range [77, 78].

The operation of a recently developed electronic wattmeter is based on the modulation of a carrier signal to achieve the multiplication of the voltage and current signals. Measurements of good accuracy on broadband, medium-level power have been reported. The device now covers the frequency range from d-c to 71 kc/s, but the extension of its coverage to higher frequencies is possible [79].

5.4. Cathode-Ray-Tube Wattmeters

The cathode-ray oscilloscope (cro) may be utilized in a power-measuring device that gives good qualitative indication of power level and phase angle up to about 30 Mc/s [1, 71, 80]. Higher frequencies may be observed with the traveling-wave cathode-ray tube [81]. The input to the cathode-ray tube is arranged so that the horizontal and vertical deflections are proportional, in turn, to the r-f current and voltage at the load (see fig. 24). The power may be shown to be

$$P=KFAC, \tag{35}$$

where K is a constant, F is the frequency, A is the area enclosed by the trace on the cro screen, and C is the value of capacitor C_1. The cro wattmeter has the advantage of instantaneous visual indications but has limitations of moderate accuracy, frequency dependence, and limited power range.

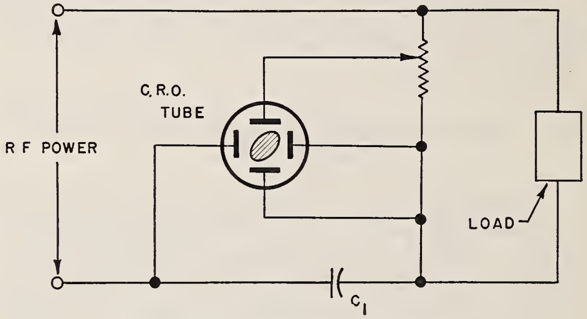

Figure 24. *Cathode-ray wattmeter.*

6. Directional Couplers

The electric field in a transmission line can, in general, be resolved into forward and reflected components. Any indicator sensitive only to one of these components may be termed a directional coupler [4, 82, 83, 84]. The voltage component associated with the forward going (toward the load) wave, V^+, and the voltage component associated with the reflected wave, V^-, may be used to determine the degree of match of the load to the line and the power transmitted to the load by the equations

$$\Gamma=\frac{V^-}{V^+} \tag{36}$$

$$\rho=\frac{1+|\Gamma|}{1-|\Gamma|}=\frac{V_{\max}}{V_{\min}} \tag{37}$$

$$P=P^+-P^-=\frac{(V^+)^2}{R_0}-\frac{(V^-)^2}{R_0}, \tag{38}$$

where Γ is the reflection coefficient, ρ is the voltage standing wave ratio, P is the power delivered to the load, R_0 is the characteristic impedance of the line, and $V_{\max}$ and $V_{\min}$ are, respectively, the maximum and minimum values of the rms voltage on the line.

The characteristics of a directional coupler are defined by the parameters "directivity" and "coupling":

$$D=10\log_{10}(P_f/P_b)$$

$$C=10\log_{10}(P_i/P_f)$$

where P_i is the power associated with the selected component on the transmission line, P_f is the power coupled into the measuring circuit from P_i, and P_b is the power coupled into the measuring circuit from the unwanted component (adjusted in magnitude to be equal to P_i).

The error in the measurement of the reflection coefficient caused by the directivity of the coupler is given to a close approximation by

$$\Gamma_x'=\Gamma_x+\Gamma_D e^{i\alpha},$$

where $\Gamma_D=\sqrt{P_b/P_f}$. Γ_x' is the measured value of reflection coefficient, Γ_x is the true value of the reflection coefficient, and α takes care of any possible phase difference [4]. Commonly encountered values of coupling and directivity are seldom less than 20 db, but for laboratory work, values of directivity as high as 60 db may be desired.

The wave-form considerations discussed in section 4 apply to eq (38). Most commercially available devices utilize germanium crystals in peak-reading circuits; it is, therefore, essential, when using such devices, that all harmonics be eliminated with suitable filters and that modulation be reduced as much as possible.

Where the wavelengths are small enough to allow the use of wave guides, directional couplers can be constructed based on the coupling properties of holes, coupling loops, and probes [4, 85]. At lower frequencies, where coaxial transmission lines are used, lumped constants may be employed, and their action as directional couplers may be analyzed as balanced bridges placed in the line [86].

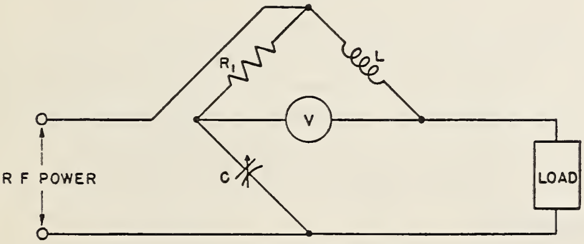

FIGURE 25. *Inductance-capacitance coupler.*

6.1. Inductance-Capacitance Couplers

The inductance-capacitance bridge illustrated in figure 25 is the basis of one instrument that is sensitive only to the reflected wave (V^-) [87]. The load and generator may be interchanged, in which case the device would respond only to the forward wave (V^+). In practice two of these bridges may be used together, one placed to read V^+, and one V^-; these values are then used to determine the voltage standing-wave ratio, or power, by eq (37) and (38). In the construction of the bridge the components must have the relationship

$$R_1R_0=L/C. \tag{39}$$

A large number of couplers have been designed utilizing the capacitance and inductance of loops introduced into the coaxial-line system [88, 89, 90, 91, 92, 93, 94, 95]. They are modifications of the inductance-capacitance-type bridge. This bridge is more convenient to construct at high frequencies than some of the subsequent types because the reactive parameters may be designed as distributed circuit elements. Devices of this nature have been constructed to measure medium and high power levels up to several hundred megacycles. Most instruments are designed for rough monitoring work and will give results of moderate accuracy.

6.2. Resistance-Capacitance Couplers

Variations of the capacitance bridge shown in figure 26 have been utilized in a large number of power and standing-wave meters [96, 97, 98]. The relationship between the components is

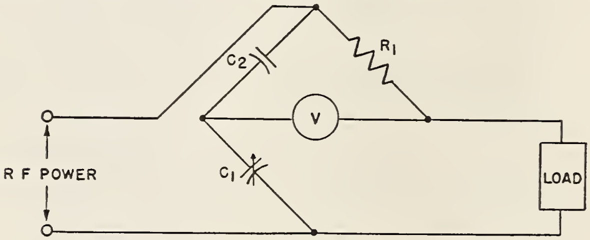

FIGURE 26. *Resistance-capacitance coupler.*

$$R_1/R_0=C_1/C_2, \tag{40}$$

and like the inductance-capacitance bridge, the balance is not frequency sensitive. In some instruments C_1 is made adjustable, so that the coupler may be matched to lines of different characteristic impedance to facilitate measurements. Devices of this nature have been built to cover the frequency range 3 to 400 Mc/s and power range 0.25 to 50,000 w and supply readings of moderate accuracy.

6.3. Resistive Coupler

The resistive type coupler is another possible variation [95, 97, 99, 100, 101]. In figure 27 two bridges are shown connected on the line in opposition, showing a similarity to the circuit of figure 19, except for component specifications. The device can be analyzed as a bridged-T attenuator, and as such should produce no power reflection when matched to the line, but its insertion loss may be undesirable in some instances. This device can be used up to about 3 Mc/s. At higher frequencies distributed capacities cause the bridge to become unbalanced. Because the resistive bridge dissipates some of the power in the line, due care must be taken against overload.

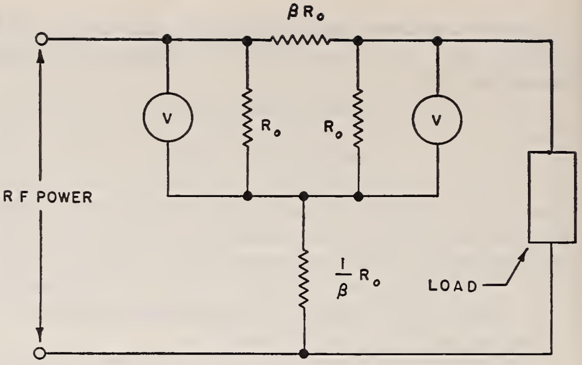

FIGURE 27. *Resistance-type coupler.*

TABLE 1. *Comparison chart*

Method	Survey section	Power range	Frequency range	Accuracy	Incident power absorbed	Time constant	Remarks
			Mc/s		*Percent*	*Sec.*	
Static calorimetry	2.1	L, M, H [a]	All	Excellent [b]	100	Up to 10^4	Fundamental type of measurement. Power level to be maintained constant over period of measurement.[c,f]
Circulating calorimetry	2.2	L, M, H	do	do	100	1	Quick response. Complicated construction.[c,f]
Adapted calorimetry	3.1	L, M, H	do	do	100	1	Simple to operate.[c,f]
Barretter	3.2	L, M	do	do	100	10^{-3}	Limited power range per unit: easy to burn out.[c,f]
Thermistor	3.2	L, M	do	do	100	10^{-1}	High sensitivity. Difficult to burn out. Very temperature sensitive.[c,f]
Photometric systems	3.3	M	0 to 300	Good	100	10^{-1}	Visual indications.[c,f]
Temperature-limited diodes	3.4	M	0 to 300	Excellent	100	10^{-2}	High sensitivity to change in power level.[c,f]
Thermocouples	3.5	M	0 to 300	do	100	10^{-1}	Simple instrumentation.[c,f]
Current-measuring systems	4.1	H	0 to 300	Good	100	Dependent on time constant of instrumentation.	Current measurement may be difficult.[d,g]
Voltage-measuring systems	4.2	L, M, H	0 to 10,000	do	100	do	Rugged. Wide frequency and power range per unit.[d,g]
Slotted lines	4.3	M, H	30 to 30,000	do	1	do	Slotted line must be at least a quarter wavelength long.[e,g]
Thermal wattmeters	5.2	H	0 to 2	do	10	do	Inaccurate with high vswr.[e,g]
Vacuum-tube wattmeters	5.3	H	0 to 50	Moderate	10	do	Accuracy generally dependent on tube characteristics.[e,g]
Cathode-ray-tube wattmeters.	5.4	H	0 to 30	do	1	do	Instantaneous visual presentation of power level, phase, and modulation. Quantitative determinations difficult.[e,g]
Inductance-capacitance couplers.	6.1	M, H	3 to 30,000	Good	5	do	Low power loss, may be left in transmission line.[e,g]
Resistance-capacitance couplers.	6.2	M, H	3 to 300	do	10	do	Wide frequency range per instrument.[e,g]
Resistive couplers	6.3	M, H	0 to 3	do	10	do	Moderate power loss in instrument. Sensitive to d-c as well as a-c.[e,g]

[a] L (low), 10^{-8} to 10^{-2} w: M (medium), 10^{-2} to 1 w: H (high), 1 to 10^6 w.

[b] Excellent, 2% or better: good, 2 to 5%: moderate, 5 to 10%.

[c] Matching devices are usually employed with these devices to make the load appear Z_0 and thus reflect none of the incident power or to make the load appear Z_g^* in order to determine the maximum power output of the r-f generator.

[d] The load must be made to appear equal to the characteristic impedance of the transmission line (vswr=1.00), so that voltage (or current) readings will not be a function of position.

[e] These devices will work with any load impedance. Individual units are designed for operation on a transmission line of a specific characteristic impedance, but units can be designed for any desired impedance.

[f] Within the bandwidth limitations of the matching device used, the power indicated is the sum of the power incident in the different frequency components.

[g] Complex wave-form response of these devices is a function of the instrumentation technique as well as the bandwidth of the load and r-f circuits.

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