# POWER METERS

Several kinds of power meters are employed in electrical and electronics engineering. Depending on the specific application, a unique power meter must be used. A description of the main kinds of power meters (dc power meters, ac power meters for electric power applications, and power meters for high-frequency electronic systems) follows. In electronic circuits, for the frequency range of approximately 1 Hz to 500 kHz, depending on the nature of the signal, power may be measured with instruments implementing methods similar to those employed in ac power meters for electric power applications or power meters for high-frequency.

## DC POWER METERS

The direct current (dc) power dissipated in a load resistance $R_L$ may be calculated from measured voltage across $R_L$ (with a dc voltmeter) and measured current flowing through $R_L$ (with a dc ammeter). This task may be performed in the two circuit configurations that are shown in Fig. 1. In the circuit of Fig. 1(a), the voltmeter measures the voltage drop $V_L$ across $R_L$, while the ammeter measures the sum of two currents, $I_L$, flowing through $R_L$, and $I_V$, flowing through the voltmeter. If no correction associated with $I_V$ is made, then the dc power is calculated as

$$P_{(a)} = IV_L = (I_L + I_V)V_L \tag{1}$$

If a correction for $I_V$ is made, then the power dissipated in the load, $P_L$, is calculated as

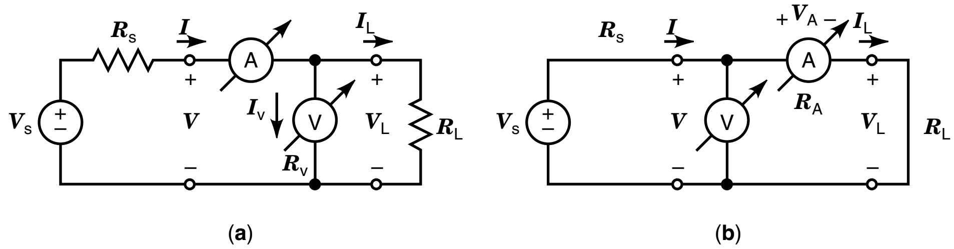
$$P_L = I_L V_L = IV_L - I_V V_L = P_{(a)} - P_V \tag{2}$$

where $P_V = I_V V_L$ is the power dissipated in the voltmeter. The worst-case relative error with which the $P_L$ is measured in the circuit of Fig. 1(a) while correction for $I_V$ is made is

$$\delta_{PL(a)} = \frac{I}{I_L}\delta_I + \delta_{VL} + \frac{I_V}{I_L}\delta_{IV} \tag{3}$$

where $\delta_I$ is the relative measurement error of $I$ (error of the ammeter), $\delta_{VL}$ is the relative measurement error of $V_L$ (error of the voltmeter), and $\delta_{IV}$ is the relative error with which the

**Figure 1.** Dc power measurement using a voltmeter and an ammeter. There are two possible measurement circuits: (a) direct $V_L$ measurement, where the voltage drop across the load is measured directly but the ammeter measures a sum of load current and voltmeter's current, and (b) direct $I_L$ measurement. The result of power measurement needs to be computed from the measured voltage and current.




$I_V$ has been estimated (calculated from known voltmeter resistance $R_V$ and measured $V_L$). If the power calculated from Eq. (1) is taken as the result of a measurement (no correction is applied), then the error of the $P_L$ in the circuit shown in Fig. 1(a) is

$$\delta_{PL(a)} = \frac{I}{I_L}\delta_I + \delta_{VL} + \frac{I_V}{I_L} \quad (4)$$

If the circuit of Fig. 1(b) is used to measure $P_L$, then the ammeter measures the current $I_L$ flowing through $R_L$, while the voltmeter measures the sum of two voltage drops, $V_L$ across $R_L$, and $V_A$ across the ammeter. If no correction related to $V_A$ is made, then the dc power is calculated as

$$P_{(b)} = I_L V = I_L(V_L + V_A) \quad (5)$$

If a correction for $V_A$ is made, then the power dissipated in the load, $P_L$, is calculated as

$$P_L = I_L V_L = I_L V - I_L V_A = P_{(b)} - P_A \quad (6)$$

where $P_A = I_L V_A$ is the power dissipated in the ammeter. The worst case relative error with which the $P_L$ is measured in the circuit of Fig. 1(b) while correction for $V_A$ is made is

$$\delta_{PL(b)} = \delta_{IL} + \frac{V}{V_L}\,\delta_V + \frac{V_A}{V_L}\,\delta_{VA} \quad (7)$$

where $\delta_{IL}$ is the relative measurement error of $I_L$ (error of the ammeter), $\delta_V$ is the relative measurement error of $V$ (error of the voltmeter), and $\delta_{VA}$ is the relative error with which the $V_A$ has been estimated (calculated from known ammeter resistance $R_A$ and measured $I_L$). If the power calculated from Eq. (5) is taken as the result of a measurement (no correction is applied) then the error of the $P_L$ is

$$\delta_{PL(b)} = \delta_{IL} + \frac{V}{V_L}\,\delta_V + \frac{V_A}{V_L} \quad (8)$$

To decide which of the two circuits is preferable, errors $\delta_{PL(a)}$ and $\delta_{PL(b)}$ need to be compared. The circuit that gives a lower measurement error is preferred. The key criterion obtained from this comparison is: which of the two ratios is smaller, $I_V/I_L$ or $V_A/V_L$?

Power meters process the information of $I_L$ and $V_L$ and display the measured power with given accuracy. Block diagrams of two dc power meters are shown in Fig. 2. The circuit shown in Fig. 2(a) implements analog multiplication of signals proportional to $V$ and $I_L$. The output voltage of an analog multiplier, $V_O$, is proportional to the product of two input voltages. In the circuit of Fig. 2(a), $V_O$ is proportional to the power dissipated in $R_L$ and may be converted to a digital form with an analog-to-digital converter (ADC), or displayed in an analog form. Analog multipliers are integrated circuits and they allow the presence of a limited voltage at their inputs. Therefore, when the input voltage $V$ is equal or exceeds the full scale value, a voltage attenuator needs to be employed. Or else, if $V$ is too small to be processed with the smallest possible error, an amplifier needs to be used. In circuits of Fig. 2, current $I_L$ is converted to voltage with a current sensor that has a low-pass frequency response (includes dc in its frequency range). The benefit of this type of current to voltage conversion is a small equivalent $R_A$ resistance. Also, the current sensor may be of clamp-on type, that makes the connection of the power meter to the circuit under test very easy.

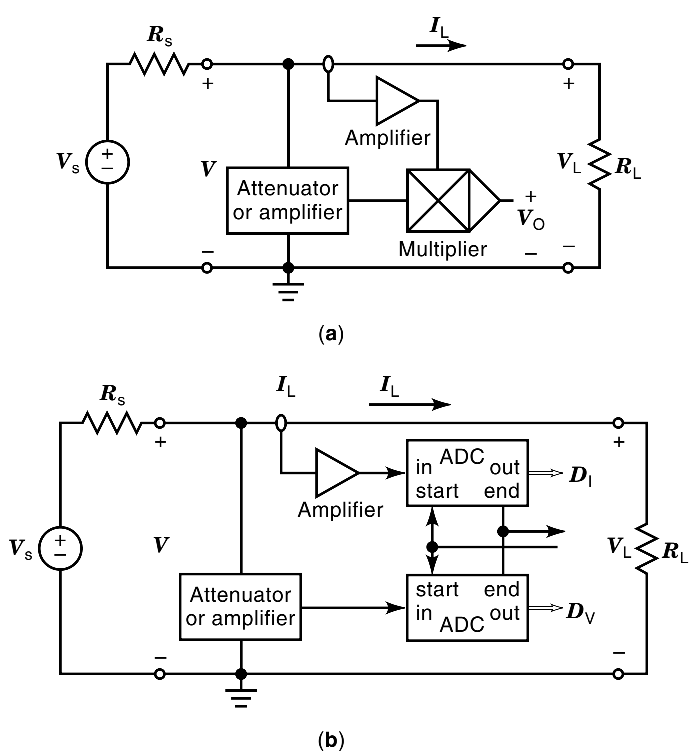



**Figure 2.** Dc power meters provide the value of measured power. One of two methods of computing the power may be employed: (a) analog power computation, (b) digital power computation.

Output voltage from current sensors is always a small value and requires amplification before it is applied to the input of the analog multiplier. Integrated circuits specially designed for applications in power measurement circuits are available. An example of such a device is the AD7750 product-to-frequency converter from the Analog Devices company (World Wide Web Site: http://www.analog.com).

The circuit depicted in Fig. 2(b) shows block diagram of a digital power meter. Instead of using the analog multiplier, voltages proportional to $V$ and $I_L$ are converted to a digital form with ADCs. Digital values $D_V$ and $D_I$ proportional to $V$ and $I_L$ are then processed by the digital part of the power meter. The circuit shown in Fig. 2(b) uses two ADCs, but sometimes one DAC and an analog multiplexer in front of it may be used.

Measurement errors of circuits shown in Fig. 2 are computed similarly as errors for the circuit shown in Fig. 1(b); see Eqs. (5) to (8). An equivalent voltage $V_A$ (or equivalent $R_A$) may be specified for the current sensor as for an ammeter.

## AC POWER METERS USED IN ELECTRIC POWER APPLICATIONS

Instantaneous power $p$ is a product of current $i$ and voltage $v$ that are functions of time $t$

$$p(t) = i(t)v(t) \tag{9}$$

Fig. 3(a) shows sinusoidal $i(t)$ and $v(t)$ as functions of phase angle $\omega t$. In the graph, the phase shift of $v$ is assumed to be 0° and current $i$ lags the voltage by 50° (inductive-resistive load). The power $p$ for these $v$ and $i$ is shown in Fig. 3(b). In cases when the instantaneous power is the signal that carries the desired information, circuits like those shown in Fig. 2 are used. An example of using the instantaneous power as a medium for fault detection of electric motors is described in the paper of Legowski, Ula, and Trzynadlowski (1). In order to update the circuits shown in Fig. 2 to ac applications, an ac voltage source with Thévenin equivalent impedance $Z_S(s)$ needs to be used in place of the dc voltage source. As the load in ac circuits an impedance $Z_L(s)$ rather than $R_L$, needs to be used. All symbols of voltages and currents need to be changed to those that represent ac signals. In these modified circuits, the output voltage from the block "Attenuator or Amplifier" is proportional to $v(t)$ and the output voltage from the block "Amplifier" is proportional to $i_L(t)$. In the ac circuit similar to the one shown in Fig. 2(a), the output voltage from the analog multiplier is $v_o(t)$ and is proportional to $p(t)$. While using this circuit, the $v_o(t)$ is further processed in an analog circuit or sampled with an ADC and processed digitally. In the ac circuit similar to the one shown in Fig. 2(b), output voltages from the "Attenuator or amplifier" and "Amplifier" are sampled with ADCs at a sampling frequency suitable for the digital signal processing of the $p(t)$. In both circuits, the bandwidth of the current sensor, "Attenuator or amplifier," and "Amplifier" must match the bandwidths of $v(t)$ and $i_L(t)$. In order to recall the other definitions of power in ac circuits, assume that the excitation is sinusoidal and the circuit is linear. Thus phasor analysis may be used. Definition of the complex power is

$$\underline{\boldsymbol{S}} = \frac{1}{2}\underline{\boldsymbol{V}}\,\underline{\boldsymbol{I}}^* \tag{10}$$

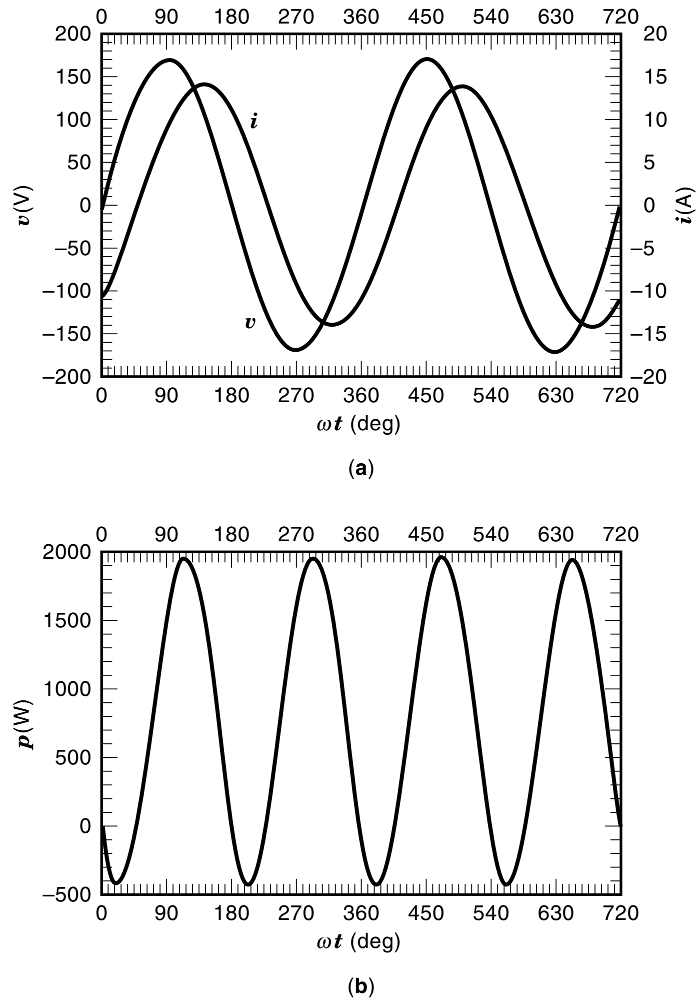



**Figure 3.** Ac voltage, current, and instantaneous power, (a) sinusoidal $v(t)$ and $i(t)$, (b) instantaneous power $p(t)$. Instantaneous power is a function of time and may take positive or negative values.

which results in

$$\underline{\boldsymbol{S}} = P + jQ \tag{11}$$

where $P$ is the active power (or real power, or average power), and $Q$ is the reactive power. A phasor diagram that shows a superposition of current, voltage, and power phasors is shown in Fig. 4. This phasor diagram shows a specific case for which the phase shift of the voltage is equal zero. The active power and reactive power are

$$P = \frac{1}{2}V_p I_p \cos\Theta \quad [W] \tag{12}$$

and

$$Q = \frac{1}{2}V_p I_p \sin\Theta \quad [VAR] \tag{13}$$

where $V_p$ is the peak value of the voltage, $I_p$ is the peak value of the current, and $\Theta$ is

$$\Theta = \phi_V - \phi_I$$

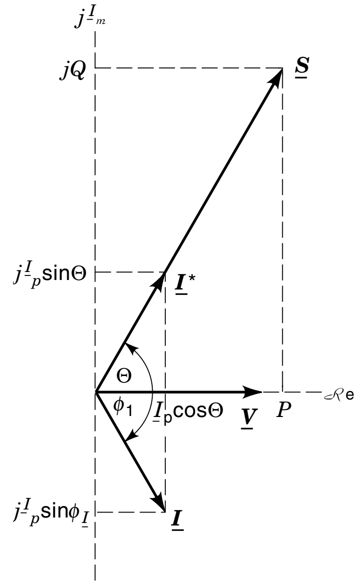



**Figure 4.** Phasor diagram of voltage, current, and power.

In the last equation, $\phi_V$, is the phase shift of the voltage, and $\phi_I$ is the phase shift of the current. The apparent power is the magnitude of $\underline{\boldsymbol{S}}$

$$|\underline{S}| = \sqrt{P^2 + Q^2} = \frac{1}{2} V_p I_p \quad [VA] \tag{14}$$

A graph of various components of ac power in the time domain (as functions of phase shift $\omega t$) is shown in Fig. 5. As before, $\phi_V = 0°$ and $\phi_I = -50°$ have been chosen for the figure. In this figure, two components of $p(t)$ are shown, $p_P(t)$ representing the energy flow into the load impedance, and $p_Q(t)$ which characterizes the energy borrowed and returned by the load impedance. The real power $P$ is at the same time the average value of $p(t)$ and also the average value of $p_P(t)$. The reactive power $Q$ is the peak value of $p_Q(t)$, while the average value of $p_Q(t)$ equals zero. The apparent power $|\boldsymbol{S}|$ equals one half of the peak-to-peak value of $p(t)$. A description of power in ac circuits may be found in the book by Cunningham and Stuller (2).

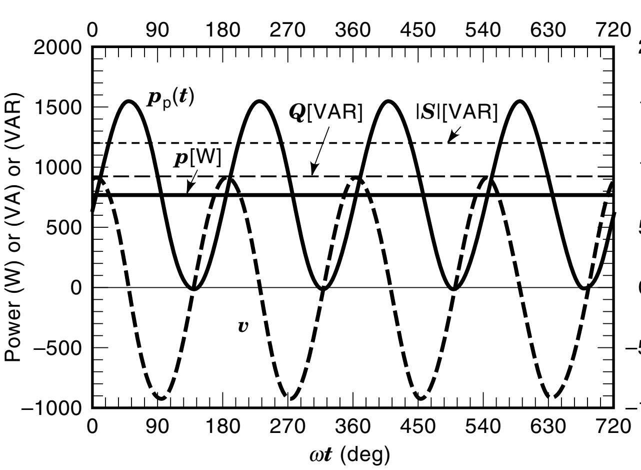



**Figure 5.** Components of ac power in time domain.

Ac power meters are designed to measure individual components of the ac power (including power factor, PF = cosΘ) or given sets of these components. The electrodynamic instrument (or dynamometer, or electrodynamometer) is the moving coil instrument that measures active power. The main parts of its mechanism are shown in Fig. 6(a). Between 1843 to 1910, the work of researchers like Wilhelm E. Weber, Lord Kelvin, James P. Joule, Andre Marie Ampere, and the brothers Werner and William Siemens made possible the development of a reliable electrodynamic instrument that started to be mass manufactured. In it, the magnetic field is produced by a two-part fixed coil conducting current $i_f$. This magnetic field and current $i_m$ in the moving coil produce a torque that turns the moving mechanism of the meter. Fig. 6(b) depicts a circuit in which ac power is measured [similarly as shown in Fig. 1(b)] with the electrodynamic instrument. The average value of the torque is

$$T_m = \frac{1}{T} \int_0^T i_m i_f \frac{dM}{d\alpha} \, dt \tag{15}$$

where $M$ is the mutual inductance between the moving and fixed coils, $\alpha$ is the angular deflection of the moving coil, and

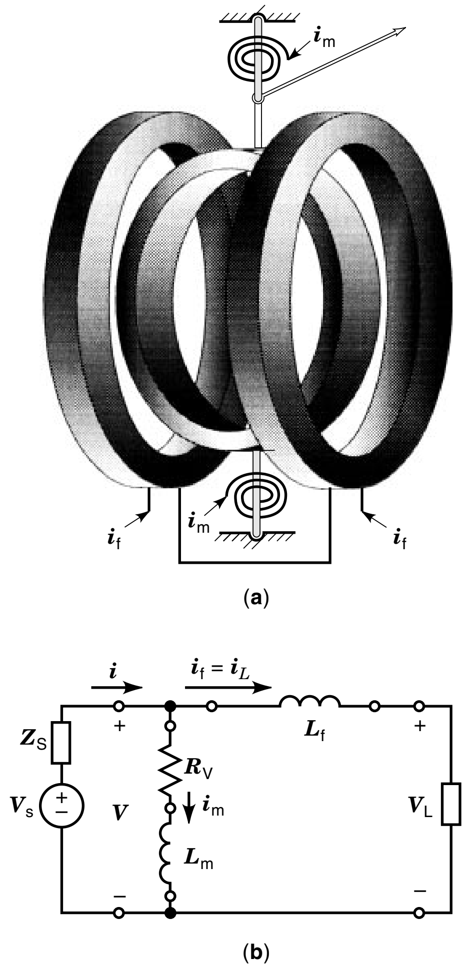



**Figure 6.** Electrodynamic power meter. Inductance $L_f$ is formed by a series connection of two inductors. Rotating inductor $L_m$ is placed in the middle of these two inductors.

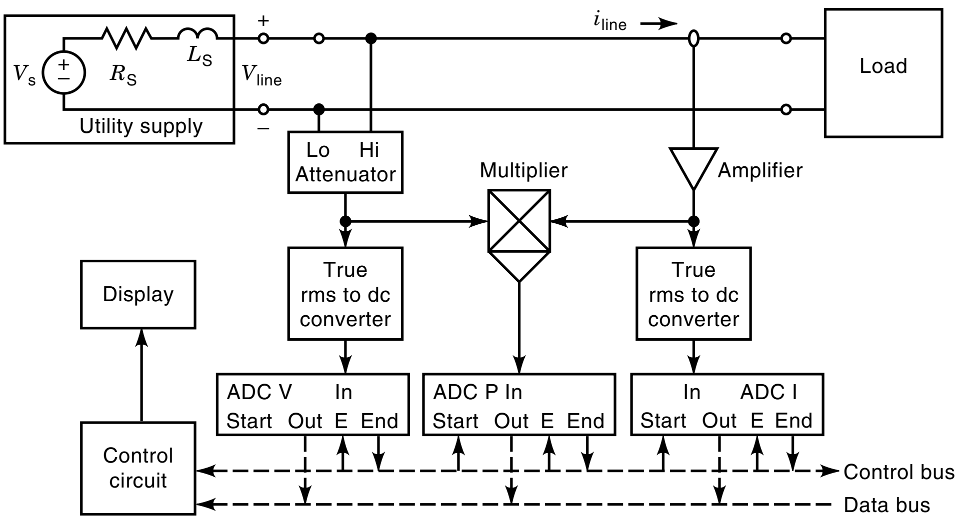



**Figure 7.** Single phase electronic power meter with analog computation circuit. The output voltage from the multiplier is proportional to the instantaneous power. Digital output of the integrating analog to digital converter is proportional to the average power.

$T$ is the period of $i_f$ and $i_m$. In series with the moving coil is connected a reference resistor $R_V$ that makes the current $i_m$ proportional to the voltage $v$. Current $i_m$ is carried to the moving coil by two control springs (that produce the reference restoring torque) and the shaft of the moving mechanism. The position of the pointer that is attached to the shaft of the moving mechanism is read from a scale in watts. The electrodynamic instrument can measure dc power. When ac power is measured, the averaging effect of the $T_m$ is produced by the inertia of the moving mechanism. Therefore, it is not possible to measure the power at frequencies below 10 Hz or so, because the averaging effect is not in place yet. On the other hand, the electrodynamic instrument may be used for frequencies up to 400 Hz. These instruments are optimized for measurements at 50 Hz or 60 Hz and may be used for sine wave signals with limited nonlinear distortions (harmonics of the line current up to the seventh harmonic are included in their frequency range). Measurement error of these instruments is usually in the range from 1% to 5% when the measured power equals the full scale value. When smaller than full scale values are measured, the measurement error increases accordingly. Other types of power meters that convert electric power to deflecting torque, for example, electrostatic wattmeters or moving-iron wattmeters, were also developed. Meters of other components of electric power, for example, power-factor meters and reactive power meters (varmeters), have been developed too. More information on torque based measurement instruments may be found in books by Kidwell (3) and Kinnard (4).

Figure 7 shows the block diagram of single phase electronic power meter. This instrument measures a set of components of the ac power that includes true rms values of line current and line voltage and the active power. The electronic power meter shown in Fig. 7 uses analog integrated circuits to convert the line current and voltage to their rms values and to produce a signal proportional to the instantaneous power. The ADCs in this type of wattmeter are of the integrating type (similar to those used in digital multimeters). The integrating ADC converts the output voltage from the analog multiplier, that is, proportional to the instantaneous power, to its average value over the time of integration, that is, to the active power. The power factor may be computed from these measurements using Eq. (12) if $v_{line}$ and $i_{line}$ are sinusoidal. Also, reactive power and apparent power may be computed.

Electronic power meters are digital instruments. An example of this class of power meters are the instruments developed by Valhalla Scientific (5) and Fluke (6,7). They are more accurate than electrodynamic instruments, measure more than one component of power, and have several ranges of measured quantities. Electronic power meters may measure active power in the range from 1 mW to 12 kW, voltage from 1 V to 600 V, current from 0.1 mA to 20 A. They have much better frequency characteristic than the electrodynamic instrument. Electronic wattmeters can be used for measuring dc power and ac power from 20 Hz to 500 kHz. They have the total measurement uncertainty from 0.1% to 0.5% of reading for frequencies up to 5 kHz or 10 kHz. For frequencies larger than that the uncertainty deteriorates, and is from 2% to 5% at 20 kHz. It worsens further for increasing frequencies. Electronic power meters may be used when the current's crest factor is in the range from 2.5 : 1 to 50 : 1, depending on the ratio of the rms value of the measured current to the full scale value. The smaller this ratio is, the larger the crest factor may be.

In the circuit of Fig. 7, a Hall effect current sensor is used. There are three types of current sensors: (1) resistive shunt (for currents lower than 500 A), (2) current transformer, and (3) Hall effect device. Two kinds of resistive shunts are made, for frequencies up to 100 Hz and for frequencies exceeding 500 kHz. Among the advantages of the resistive shunt current sensors are: they convert dc and ac current, are very reliable, do not produce offset voltage, and those made for frequencies below 100 Hz are not expensive. To the disad vantages of these current sensors belong: a lack of electrical isolation from the line voltage, significant power loss, they require amplification of the output voltage, those made for frequencies exceeding 500 kHz are expensive. Current transformer type sensors may sense currents up to 100 kA and their output current may be easily converted to voltage. Their advantages include: electrical isolation from the line voltage, they are very reliable, and low cost. The disadvantages are: they sense ac current only, the power loss is not negligible, their output current is frequency dependent, and they are susceptible to

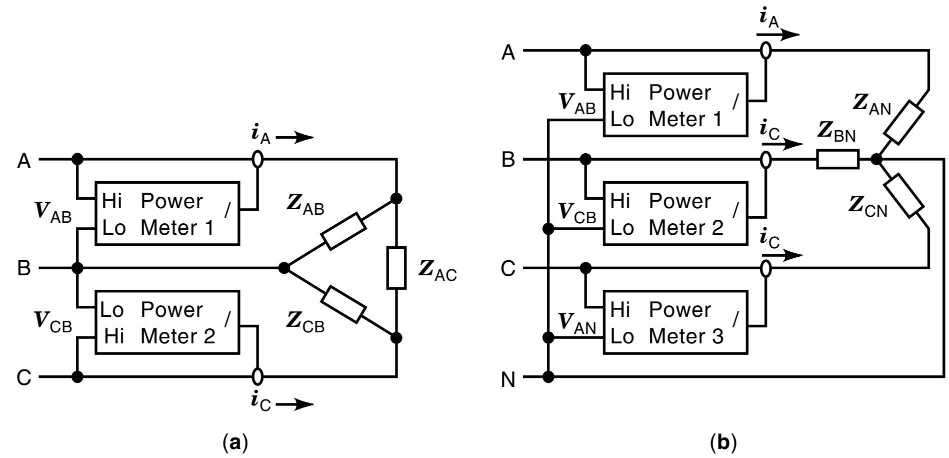



**Figure 8.** Three phase power measurement circuits: (a) circuit for Δ connected load or two power meter circuit, and (b) circuit for Y connected load with neutral line or three power meter circuit.

stray ac magnetic fields. The Hall effect current sensors can measure dc and ac currents. They provide electrical isolation from the line voltage, may measure large currents (3 kA or so), some have bandwidth from dc to 200 kHz, and they are very reliable. The disadvantages include: they require external power supply and the output signal includes an offset that needs to be compensated. An electronic power meter may include resistive shunt current sensors. In such a case, the range of the current input may be increased up to a few kiloamperes by using additional current transformers. However, use of current transformers increases the measurement error by about 1% or 2% and the frequency range will be limited to a range from 40 Hz to about 400 Hz. More information on current sensors is provided in the paper written by Drafts (8).

Figure 8 shows circuits for three phase power measurements with single-phase power meters. The circuit shown in Fig. 8(a) is used when the load is Δ connected and only three phase lines are used. In such a case two power meters are used. Inputs to "Power meter 1" are $i_A$ and $v_{AB}$, while inputs to "Power meter 2" are $i_B$ and $v_{CB}$. Power delivered to the three phase load is

$$P_{3\Phi 3W} = P_1 + P_2 \quad [W] \tag{16}$$

where $P_{3\Phi 3W}$ is the total active power measured in the three-phase, three-wire circuit, $P_1$ and $P_2$ are the active powers measured by "Power meter 1" and "Power meter 2", respectively. Figure 8(b) shows the measurement circuit used when in addition to the three phase lines the neutral conductor is used. Three power meters are used in such a case. Inputs to the "Power meter 1" are $i_A$ and $v_{AN}$, inputs to the "Power meter 2" are $i_B$ and $v_{BN}$, and inputs to the "Power meter 3" are $i_C$ and $v_{CN}$. The power delivered to the three phase load is

$$P_{3\Phi 4W} = P_1 + P_2 + P_3 \quad [W] \tag{17}$$

where $P_{3\Phi 4W}$ is the total active power measured in the three-phase, four-wire circuit, $P_1$, $P_2$, and $P_3$ are the active powers measured by "Power meter 1", "Power meter 2", and "Power meter 3", respectively.

In many cases, for example, when adjustable speed drives are used to drive electric motors, the line current is not sinusoidal at all. An adjustable speed drive may be supplied from a single phase line (this is not a typical case), as it is shown in Fig. 9(a), or from a three-phase line, as shown in Fig. 9(b). An adjustable speed drive contains a rectifier with a huge capacitance at its output and an inverter that converts the dc supply to adjustable frequency three-phase supply. Because of this huge capacitance the line current $i_{line}$ has a form of relatively narrow pulses. An oscillogram of $i_{line}$ of a single phase inverter is shown in Fig. 10(a) and spectrum of it is shown in Fig. 10(b). Because $i_{line}$ may be of the nature shown in Fig. 10(a), one of the important parameters of a power meter is the maximum acceptable crest factor of the current. A power meter usually has an indicator in the form of a light-emitting diode (LED) that warns the user when the current has too large of a crest factor and the measurements are unreliable. An example of waveforms on the output from the "Adjustable speed drive" that drove a 60 hp induction motor are shown in Fig. 11(a) and (b). The inverter used in the adjustable speed drive that produced these signals was a voltage source type and the direct torque control was used in it. Line-to-line voltages at the output of this drive are pulse trains, as shown in Fig. 11(a). Because an inductive load is driven by the drive, the current waveform is similar to the integral of the voltage and are sinusoidal with a ripple component, as shown in Fig. 11(b). Fig. 11(c) shows the spectrum of the line current. An analysis of the graphs shown in Fig. 11 makes it clear that high-bandwidth instruments must be used to measure the output power of the "Adjustable speed drive" shown in Fig. 9. Electronic instruments called power analyzers are used to make these measurements. They are capable to measure power delivered to the "Adjustable speed drive" (rectifier with a large capacitor on its output), as well as the output

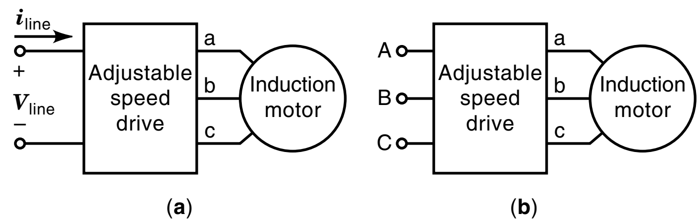



**Figure 9.** Adjustable speed motor drives: (a) motor drive with single phase input or single phase or three phase converter, (b) motor drive with three phase input or three phase to three phase converter.

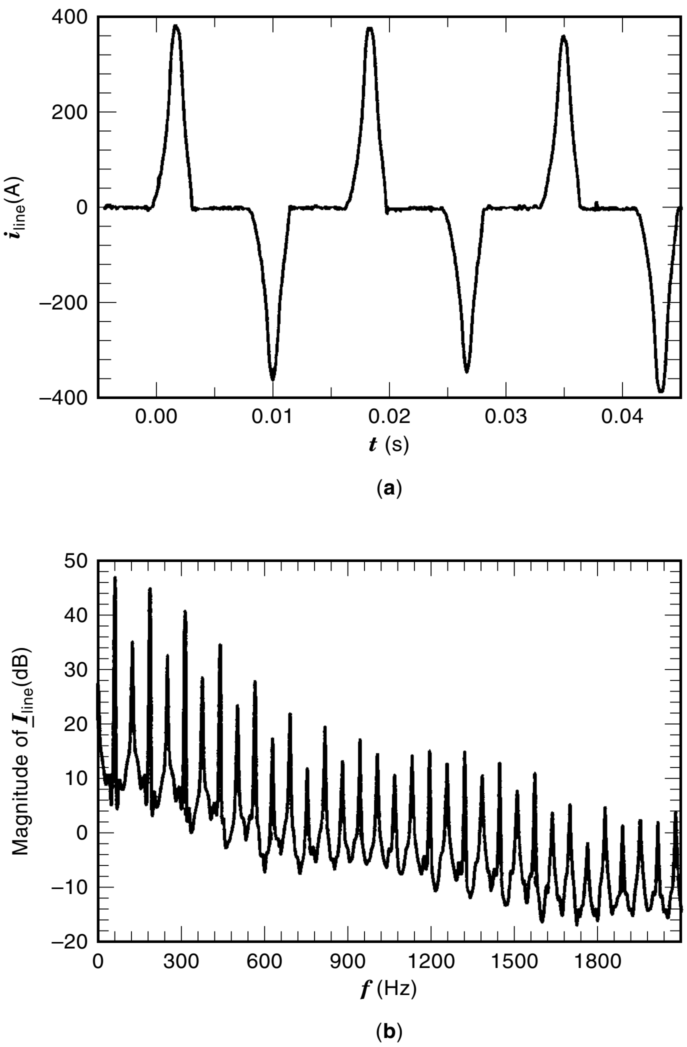



**Figure 10.** Line current of an adjustable speed drive, (a) timing diagram, (b) spectrum.

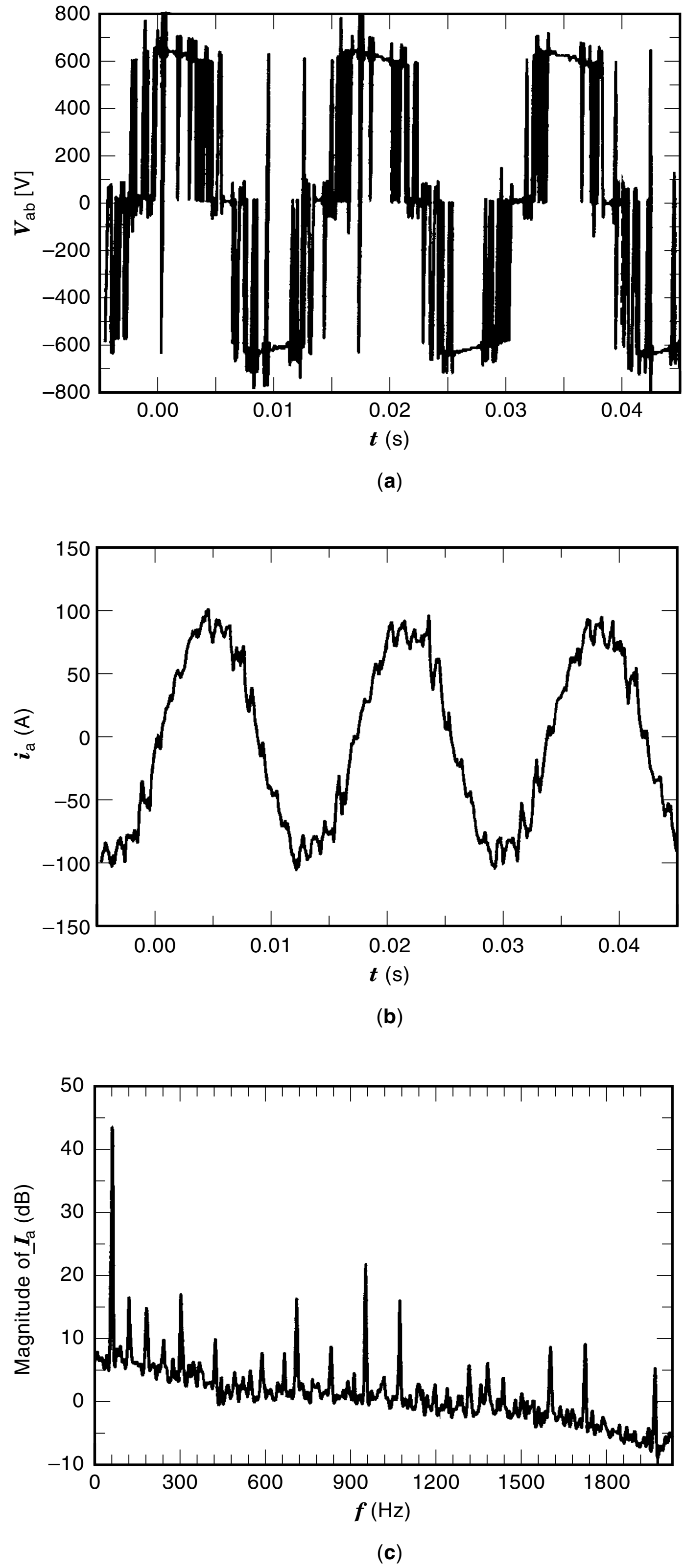



**Figure 11.** Line-to-line voltage and line current of an adjustable speed drive, (a) line-to-line voltage, (b) line current, (c) spectrum of line current.

power of the "Adjustable speed drive." A block diagram of a power analyzer is shown in Fig. 12. It has three input channels, but it may be used in any configuration, from single-phase power meter to three-phase, three-wattmeter measurement system. Current inputs accept various current sensors. Signal-processing methods are used to compute all components of three phase power, including spectrum analysis of line currents. Every channel has a "Programmable attenuator" and "Programmable amplifier" for matching the signal levels with the ranges of ADCs. These ADCs sample the signals with sampling frequency that is required for processing signals like these shown in Figs. 10 and 11. Every programmable attenuator/amplifier with its ADC is supplied by a floating power supply, because its input is connected to a three-phase system. Digital signals from every programmable attenuator/amplifier are transmitted through isolation circuits to the digital signal processing (DSP) system, where the signal processing takes place. Power analyzers may be used as instruments in a measurement system using the IEEE-488 Bus or connected to a computer using the RS-232-C transmission line. Power analyzers measure active power, reactive power, apparent power, power factor, rms value of voltages

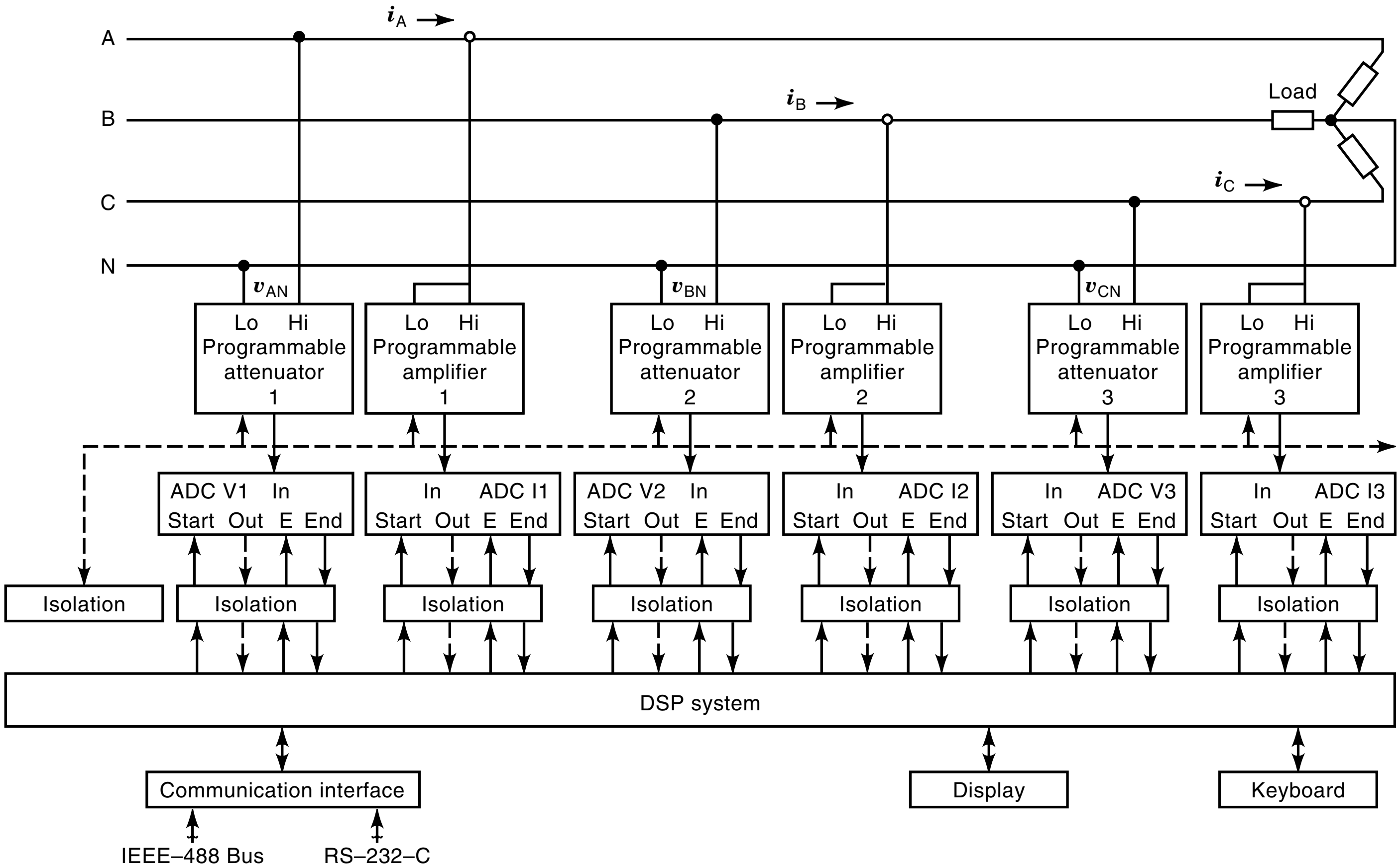



**Figure 12.** Three phase electronic power analyzer using digital computation method. Successive approximation digital to analog converters are used to acquire samples of phase voltages and phase currents. Signal processing is used to compute parameters of a three phase system.

and currents, peak values of voltages and currents, crest factor of voltages and currents, peak inrush current, impedance, spectrum of voltages and currents (fundamental frequency, up to 99th harmonic, and total harmonic distortion), and integrals of active and reactive power (Whr and Varhr). Active power range is from 25 mW to 400 kWp, voltage range is from 0.5 V to 2 kVp, current range is from 50 mA to 200 Ap, frequency range from 0.1 Hz to 500 kHz. Measurement uncertainty is usually in the range from 0.05% to 0.2% of the reading. An example of this kind of instrument is the Voltech power analyzer (9).

Example of a measurement circuit for efficiency measurements of induction motors driven by the "Adjustable speed drive" is shown in Fig. 13. This kind of measurements must follow requirements described in appropriate standards, for example, IEEE Std.112, and it is feasible to make these measurements in a computer-controlled system, as shown in Fig. 13. In this system, as the load of the motor under test a programmable dynamometer made of a dc generator with digitally controlled field current is used. The dynamometer is adjusted to the required power range by changing the load of the dc generator. The input power is measured with the power analyzer, while the mechanical power is measured with the torque measurement system. Measurement of temperature in up to 8 points of the motor under test is necessary in some measurement protocols.

## MECHANICAL POWER METERS

A block diagram of a mechanical power meter used in the measurement system of Fig. 13 is shown in Fig. 14. A torque transducer is inserted in the shaft connecting the motor under test with the dynamometer. The torque transducer consists of a reference part of the shaft (reference diameter and material) with a strain gauge bridge ($R_1$, $R_2$, $R_3$, and $R_4$) affixed to its surface in such a way that the output signal from the bridge is proportional to the torque. The bridge is used as an ac bridge at carrier frequency in the range from 1 kHz to 20 kHz. Supply voltage to this bridge and the output signal from the bridge are transmitted between the stationary measurement system and the rotating shaft with two rotary transformers. The ac bridge is used because of very large interference of noise to the sensing part of the meter. The output voltage from the bridge is a very low level signal, hence a large voltage gain amplifier must be used before the signal can be rectified with the synchronous demodulator. The synchronous demodulator uses a reference voltage from the same oscillator that produces the excitation for the bridge and has the ability of rejecting dc offset and the noise, and passing only the signal of frequency of the oscillator. As the synchronous demodulator the integrated circuit AD630 from Analog Devices, described in the Analog Devices databook (10), may be used. The signal from the oscillator that is used as the

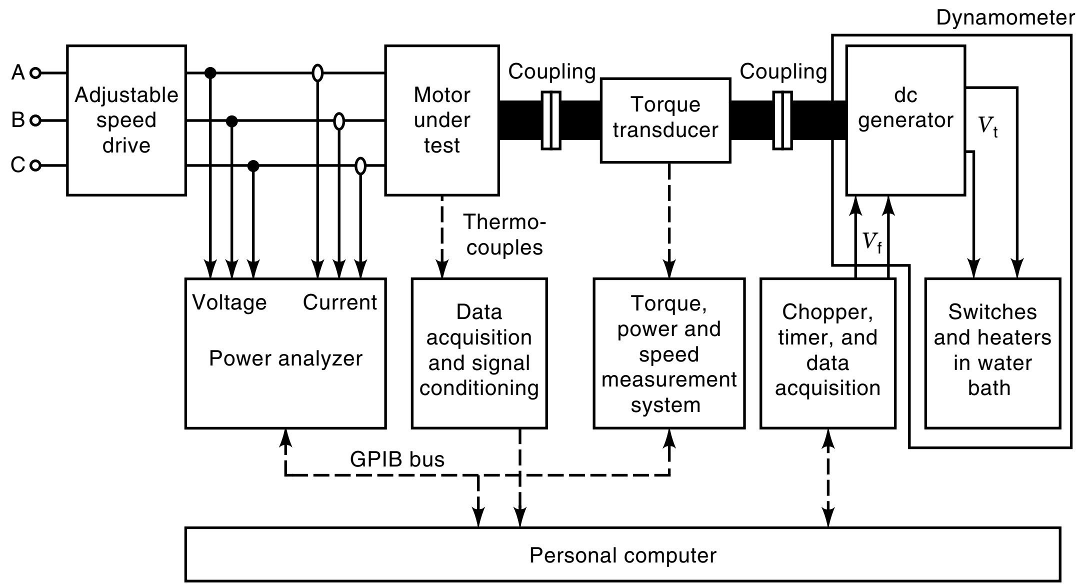



**Figure 13.** Automatic system for measuring efficiency of electric motors. The dc generator is used as a programmable load for the motor under test. Various test programs may be carried out in this system.

reference for the synchronous demodulator must have its phase shift adjusted accordingly with the phase of the output signal from the bridge. The dc value of the output voltage from the synchronous demodulator (average value of the output voltage) carries the information of changes of resistances of the bridge. The dc value of the output voltage from the synchronous demodulator is obtained by using a low-pass filter. The AD630 with ease allows the measurement of change of bridge resistances of 0.5 ppm, which corresponds to a 3.2 mV change in the output voltage from the low-pass filter. The dc output voltage from the low-pass filter is proportional to torque. This output voltage is converted to a corresponding digital value with the ADC. In addition to torque, the velocity of the shaft is measured and the results are stored in the microprocessor system. Mechanical power is computed in the microprocessor system based on the measured torque as

$$P_m = \frac{V_{avg}T}{63025} \tag{18}$$

where $P_m$ is the mechanical power in horsepower, $T$ is the torque in pounds per inch, and $V_{avg}$ is the average shaft velocity in revolution per minute. An example of the mechanical power meter is the torque transducer and mechanical power instrument from the Himmelstain company (11).

## POWER METERS FOR HIGH FREQUENCY (HF) ELECTRONIC SYSTEMS

Electronic systems employ a very wide frequency range, from dc to hundreds of gigahertz, and a great variety of waveforms, ranging from continuous wave (CW unmodulated and modulated sinewaves) to complex pulse trains. Values of measured power range from tenths of picowatt to several kilowatts. A number of measurement methods are used to measure the power of these diverse signals. In electronic systems that operate in the radio frequency (RF) and microwave frequency ranges from about 100 kHz to 110 GHz, active power is the

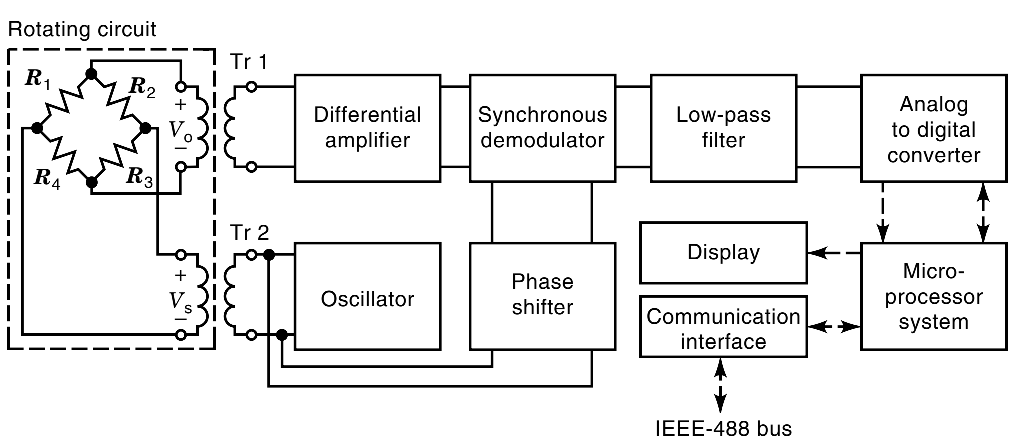



**Figure 14.** Mechanical power meter for measurement of power transmitted by a shaft. A torque transducer that includes a rotating strain gauge bridge needs to be installed in the shaft.

most frequently measured quantity. In this frequency range, power meters belong to the group of typical instruments used for evaluating electronic systems. An HF power meter consists of a power sensor, which converts active power of a RF or microwave signal to a dc or low-frequency signal proportional to the active power and a power meter (also called an RF meter). For a given kind of signal and its range of frequency, a right power sensor must be selected from a set of more than twenty different kinds of power sensors. One power meter may work with a few power sensors that were designed specifically for this power meter. Therefore, power sensors and the power meter must be of the same brand, say Hewlett-Packard or Rhode & Schwartz. Three methods of power sensing are used and they are described below. Results of power measurements are expressed as absolute power in watts (W) or as relative power in dBm. The definition of dBm is

$$\text{dBm} = 10\log_{10}\left(\frac{P}{1\text{mW}}\right) \tag{19}$$

where the active power $P$ is expressed in milliwatts. The active (or average) power in RF and microwave power measurements is averaged over many periods of the signal and is defined as

$$P_{\text{avg}} = \frac{1}{nT_l}\int_{t_0}^{t_0+nT_l} v(t)i(t)\,dt \tag{20}$$

where $T_l$ is the period of the lowest frequency component of $v(t)$ and $i(t)$. The averaging time is typically in the range from several hundredths of a second to a few seconds and is much greater than $T_l$; therefore it is not essential to integrate over an integer number of periods of $v(t)$ and $i(t)$. For pulse type signals, the pulse power is defined as

$$P_{\text{P}} = \frac{1}{\tau}\int_{t_0}^{t_0+\tau} v(t)i(t)\,dt \tag{21}$$

where $\tau$ is the pulse width, defined as a time from the instance when the rising edge rises to 50% of the pulse amplitude to the instance when the falling edge falls to 50% of the pulse amplitude. Two envelopes of power pulses are shown in Fig. 15. The envelope of power shown in Fig. 15(b) represents a pulse train of single periods of the function $[1 - \cos(\omega\mathbf{t})]$. This shape of pulses has been chosen because it is easy to envision the three values of power for this signal [which are depicted in Fig. 15(b)]. Measurements of pulse power as defined by Eq. (21) are difficult to perform, therefore another definition of the pulse power is also used:

$$P_{\text{Pa}} = \frac{P_{\text{avg}}}{DT} \tag{22}$$

where DT is the duty cycle defined as

$$DT = \frac{\tau}{T} \tag{23}$$

Only for a rectangular power envelope $[p_e(t)]$ such as the one shown in Fig. 15(a) will the definitions described by Eqs. (21) and (22) give the same result. For the particular power envelope shown in Fig. 15(b), the peak value of $p_e(t)$ equals $P_{pa}$. For many practical kinds of power envelopes, as for example, Gaussian pulse shape used in certain navigation systems, the peak value of $p_e(t)$ is not equal $P_{pa}$. Power meters for many other kinds of complex signals, like fast digital phase-shift-keyed modulation or multiple carrier signals, are also available. Proper selection of a power sensor and power meter adequate for the specific kind of measured signal is a critical factor in accurate power measurements.

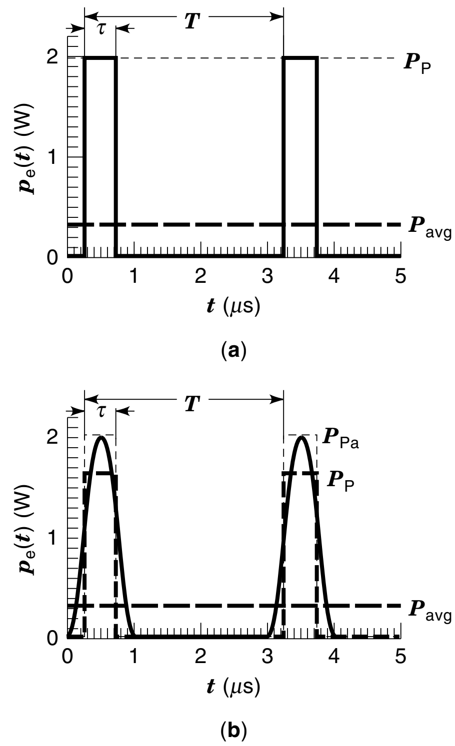



**Figure 15.** Envelopes of power pulses, (a) rectangular power pulses, (b) sinusoidal power pulses.

The measured power may be the terminating power, that is the power absorbed in a load, or directional power, that is forward or reflected power. For measuring the terminating power, the measurement usually made, the power sensor is used in place of the load. The readout from the power meter is affected by errors related to inaccuracies of:

1. the HF part of the circuit, because the HF power dissipated in the power sensor is slightly different from the power that would be dissipated there if everything in the circuit is perfect (in the description that follows, the perfect parameters are called “ideal”)
2. the circuit that produces dc or low frequency power equal to the HF power dissipated in the power sensor (this function is performed by a closed loop control system)
3. the measurement circuit of the dc or low frequency power

Denote the HF power actually dissipated in the load (the HF power dissipated in the power sensor) as $P_l$ and the ideal amount of power that would be dissipated there when the Hf part of the circuit is perfect as $P_{l,\text{ideal}}$. The relationship between $P_l$ and $P_{l,\text{ideal}}$ is

$$P_l = \frac{1 - |\Gamma_l|^2}{|1 - \Gamma_s \Gamma_l|^2} P_{l,\text{ideal}} \tag{24}$$

where $\Gamma_l$ is the reflection coefficient of the load (a complex number with magnitude $\rho_l$ and phase shift $\phi_l$) and $\Gamma_s$ is the reflection coefficient of the source (a complex number with magnitude $\rho_s$ and phase shift $\phi_s$). Denote the dc or low frequency power that substitutes the HF power as $P_{sub}$. Inaccuracy of the substitution process is represented by the effective efficiency $\eta_e$

$$\eta_e = \frac{P_{sub}}{P_l} \tag{25}$$

Recalling that

$$P_l = P_i - P_r \tag{26}$$

where $P_i$ is the incident power and $P_r$ the reflected power, and that the calibration factor $\kappa_{cal}$ is

$$\kappa_{cal} = \frac{P_{sub}}{P_i} \tag{27}$$

the following relationship between the effective efficiency and calibration factor may be written

$$\kappa_{cal} = \eta_e (1 - |\Gamma_l|^2) \tag{28}$$

If the result of the HF power measurement displayed by the power meter is denoted as $P_m$, its departure from the $P_{m,\text{ideal}} = P_{sub}$ is expressed by the equation

$$P_m = \xi P_{m,\text{ideal}} + P_{m,os} \tag{29}$$

where $\xi$ represents the gain coefficient (ideally $\xi = 1$) and $P_{m,os}$ represents the offset error ($P_{m,os}$ may be a positive or negative number, ideally $P_{m,os} = 0$). Hence, the relationship between the readout from the power meter and the ideal value of HF power delivered to the power sensor is

$$P_m = \xi \kappa_{cal} \frac{P_{l,\text{ideal}}}{|1 - \Gamma_s \Gamma_l|^2} + P_{m,os} \tag{30}$$

A more detailed description of the accuracy of HF power measurement may be found in the Hewlett-Packard Application Note 64-1A (12).

Power sensor circuits are quite complex and only basic principles of their operation are described below. Every power sensor is characterized by a set of calibration coefficients that may be stored in an EEPROM installed in the power sensor unit. The power meter reads these calibration coefficients and automatically implements them in computations of the result of a measurement. Peak power analyzers for power measurements in pulsed RF and microwave electronic systems are also available. A broader description of RF and microwave power measurements may be found in Hewlett-Packard's Application Notes 64-1A (12) and 64-4A (13). Parameters of power sensors and power meters currently available from the Hewlett-Packard company may be found in the product catalog (14) and listed there publications. Power sensors and RF meters offered by the Rhode & Schwartz company may be found in the Tektronix company's catalog of measurement products (15). The author also referred to unpublished materials written by Barp (16).

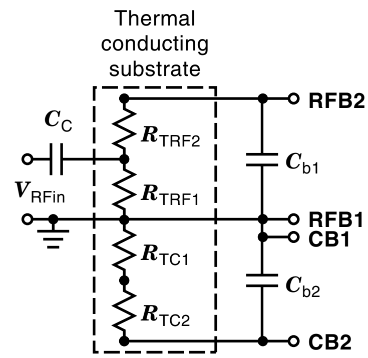



**Figure 16.** HF thermistor power sensor. Two thermistors TRF are used to convert HF power to an equivalent dc or low frequency voltage. Two thermistors TC are used to compensate for changes of ambient temperature.

### Thermistor Power Sensors and Power Meters

Bolometers are power sensors that implement devices whose resistance is a function of temperature. The increment of temperature of such a device is proportional to the increment of active power dissipated in it, no matter what kind of signal (ac or dc) is delivering the power. Hence, bolometers possess a power substitution ability that is beneficial in transferring standards. There are two types of bolometers, barretters and thermistors. A barretter is a very small power (about 10 mW) metallic resistor. Power sensors using barretters are not manufactured any more because the allowed overload of a barretter is small and its damage may readily occur. Power sensors employing thermistors are still fabricated, but they are not typical power sensors now. Their frequency range is limited and their impedance matches are not good. The main use of thermistor power sensors is as power transfer standards to references, for example, at the National Institute of Standards and Technology (NIST) in Boulder, CO, and in the round robin procedures. Thermistors are mounted in either coaxial or waveguide structures. Figure 16 shows the circuit of the RF thermistor power sensor and Fig. 17 shows the mea-

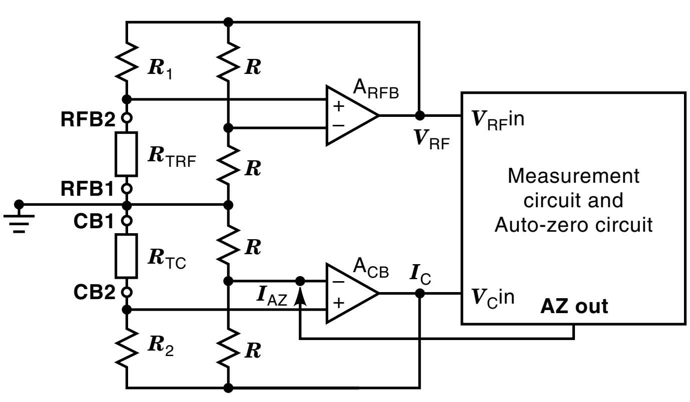



**Figure 17.** Thermistor HF power meter. This simplified circuit diagram shows a power measurement system formed by the power meter and the power sensor.

surement circuit of the power meter. Thermistors TRF1 and TRF2 are heated by the input RF signal, $v_{RFin}$, and a portion of the dc supply voltage of the measurement circuit, $V_{RF}$. The RF signal is applied through the coupling capacitor $C_C$ to thermistors TRF1 and TRF2 connected in parallel (for the RF signal, the bypass capacitor $C_{b1}$ connects the terminal RFB2 to the ground). Thermistors TRF1 and TRF2 are connected to the dc bridge measurement circuit using terminals RFB1 and RFB2, therefore in the dc bridge they are connected in series. Equivalent resistance of the parallel connection of $R_{TRF1}$ and $R_{TRF2}$ equals a matching impedance for the transmission line (50 Ω or 75 Ω). This equivalent resistance is maintained constant (temperature of TRF1 and TRF2 is maintained constant) and independent of the amount of RF power delivered to it as well as of ambient temperature variations. The dc voltage across thermistors TRF1 and TRF2 equals $0.5V_{RF}$. The power meter keeps the sum of the RF power and dc power dissipated in $R_{TRF1}$ and $R_{TRF2}$ at a constant value. In order to simplify the description, first ignore the presence of $R_{TC1}$ and $R_{TC2}$ in the circuit. For $v_{RFin} = 0$, the $V_{RF}$ has its largest value (the whole power dissipated in $R_{TRF1}$ and $R_{TRF2}$ is delivered from the dc voltage source) corresponding to the full scale power. When $v_{RFin}$ produces in $R_{TRF1}$ and $R_{TRF2}$ one half of the full scale power, then $V_{RF}$ delivers one half of the full scale power. When the $v_{RFin}$ delivers the full scale power, then the $V_{RF} = 0$. The second pair of thermocouples, TC1 and TC2, is used to compensate for variations of ambient temperature. All four thermistors are mounted on a thermal conducting substrate and they are in the same temperature. The bypass capacitor $C_{b2}$ ensures that there is no RF signal between terminals CB2 and CB1. Thermistors TC1 and TC2 are a part of the compensation bridge supplied by the dc voltage $V_C$. For $I_{AZ} = 0$, the voltage across thermistors TC1 and TC2 connected in series equals 0.5 $V_C$. Voltage $V_C$ changes when the ambient temperature changes. The resistance temperature coefficient of thermistors is negative, thus if the ambient temperature increases, the $R_{TC1}$ and $R_{TC2}$ would like to decrease. However, instead of that the $V_C$ decreases, less power is delivered from the $V_C$ and the $R_{TC1}$ and $R_{TC2}$ remain constant. The same mechanism changes $V_{RF}$ when the ambient temperature varies. Because of that, $V_{RF}$ must be larger than initially was assumed. The readout of the power meter is proportional to the difference ($V_C - V_{RF}$), hence $V_{RF}$ may be made larger than the full scale $V_{RFin}$ (rms value of $v_{RFin}$). To adjust the zero of the power meter, at $v_{RFin} = 0$ the auto-zero circuit sets the auto-zero current $I_{AZ}$ to a value for which the output voltage from the power meter, $V_{OUT}$, that is proportional to the difference ($V_C - V_{RF}$), equals zero. For increasing $v_{RFin}$ the $V_{RF}$ decreases and $V_{OUT}$ increases in proportion with the increase of $V_{RFin}$.

### Thermocouple Power Sensors and Power Meters

Thermocouples exhibit an inherent square-law transfer characteristic, where square-law means that the dc output voltage is proportional to the square of the input rms voltage across a reference resistance, that means to the input RF power. Thermocouple sensors are heat-based devices, consisting of a resistor that dissipates the measured power of any kind of an electric signal and the thermocouple that converts its temperature to a dc voltage. Thermocouple sensors allow power meters to be made with full scale power from 0.3 μW and with a small SWR (standing wave ratio). Thermocouple sensors are fabricated using combined thin-film and semiconductor technologies. A simplified circuit diagram of a thermocouple sensor is shown in Fig. 18. The bypass capacitor $C_b$ is a short circuit for RF signal, thus the $v_{RF}$ is applied to the two pairs of resistor–thermocouple connected in parallel. The equivalent resistance of this parallel connection constitutes the 50 Ω or 75 Ω termination resistance of the RF transmission line. However, from the standpoint of the dc output voltage $V_{OUT}$, these thermocouples are connected in series, hence the $V_{OUT}$ equals two times a voltage from a single thermocouple. Typical thermocouples' sensitivities are 250 μV/°C and 160 μV/mW. The transfer characteristic of the thermocouple sensor ($V_{OUT}$ as a function of $P_D$) is slightly nonlinear, because its sensitivity is a little lower for large powers. The thermocouple sensor's $V_{OUT}$ is approximately 160 nV for 1 μW of power dissipated in it, consequently the power sensor and power meter are considerably complex. Figure 19 shows a simplified block diagram of the power sensor attached to the power meter. Dc signals at such a low level as the $V_{OUT}$ cannot be transmitted over a cable. Also, in the power meter they need to be amplified significantly. A chopper amplifier is used to obtain the required large amplification of the $V_{OUT}$. One-half of the gain is provided by the ac amplifier located in the power sensor enclosure, and the other one half of the gain is furnished by an ac amplifier located in the power meter enclosure. The ac output voltage from the amplifier is demodulated synchronously with the chopping signal. An auto-zero feature is implemented in the measurement scheme too. Thermocouple sensors do not have the dc substitution feature; hence it is necessary to provide a reference RF power source for calibration purposes. The output power of this reference power source is controlled with total uncertainty better than ±1%.

### Diode Sensors and Power Meters

Schottky diodes are used to build diode sensors. *P–N* junction diodes have much smaller bandwidth than Schottky diodes, without bias have extremely high impedance, and when biased they produce a large amount of noise and thermal drift. Schottky diodes specially designed for applications in power sensors have a low potential barrier of the metal-semiconductor junction, which results in a forward voltage of about 0.3 V. They have a very large bandwidth that is within the microwave frequency range. Current–voltage (*I–V*) characteristic of these diodes may be divided into three regions: (1) the square-law region for very small voltages across the junction, (2) a linear region for large voltages, and (3) the transition

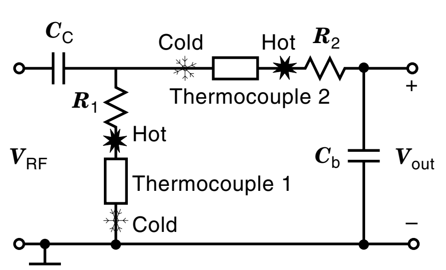



**Figure 18.** HF thermocouple power sensor. A pair of thermocouples is used to convert the HF power to an equivalent dc or low frequency voltage.

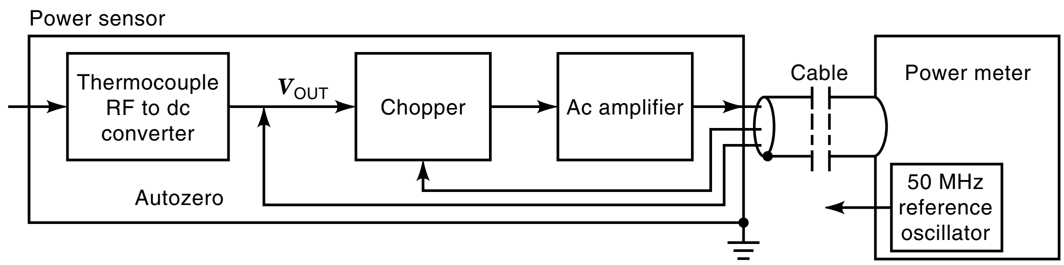



**Figure 19.** Thermocouple HF power meter. This simplified block diagram illustrates functions of the power meter that together with a HF thermocouple power sensor forms a power measurement system.

region from the square-law region to the linear region. The $I$–$V$ characteristic is described by the approximate equation

$$I = I_S\left[\exp\left(\frac{V}{nV_T}\right) - 1\right] \tag{31}$$

where $I_S$ is the saturation current, $n$ is a coefficient specific for a given type of a Schottky diode that compensates the weak dependence of the saturation current on voltage $V$ in the accurate equation, and $V_T$ is the thermal voltage

$$V_T = \frac{kT}{q} \tag{32}$$

In Eq. (32), $k$ is Boltzmann's constant, $T$ is the temperature in kelvins, and $q$ is the charge of an electron. Derivation of the Schottky diode equation may be found in the book by Muller and Kamins (17). Figure 20(a) shows the $I$–$V$ characteristic of a Schottky diode designed for power sensor applications. The constant $n$ is slightly greater than 1 and for making the graph $n = 1.07$ has been used. Schottky diodes fabricated for applications in power sensors have much larger $I_S$ than typical Schottky diodes. The exponential term in Eq. (31) may be expanded into the infinite series form

$$\exp\left(\frac{V}{nV_T}\right) - 1 = \frac{1}{1!}\frac{V}{nV_T} + \frac{1}{2!}\left(\frac{V}{nV_T}\right)^2 + \frac{1}{3!}\left(\frac{V}{nV_T}\right)^3 + \cdots \tag{33}$$

For $V \ll nV_T$ Eq. (31) may be approximated as

$$I_q = I_S\left[\frac{V}{nV_T} + \frac{1}{2}\left(\frac{V}{nV_T}\right)^2\right] \tag{34}$$

where $I_q$ is the current $I$ approximated by the quadratic Eq. (34). Figure 20(b) shows graphically the error of this approximation ($\delta$) for $-20$ mV $< V <$ $+20$ mV, defined as

$$\delta = \frac{I_q - I}{I}100\% \tag{35}$$

Figure 21 shows the simplified circuit of an unbiased diode for detecting low level RF and microwave signals. A matching resistor is used to obtain the right termination impedance for a transmission line. In practical circuits two diodes are used in the circuit of a power sensor. When the diode power sensor detects the smallest power level (limited by noise of the diode) of 100 pW the dc output voltage $V_{OUT} = 50$ nV. To handle this extremely small signal, a high-gain chopper amplifier is used in the power meter. Part of this amplifier is located in the enclosure of the power sensor, as well as circuitry for temperature compensation and the EEPROM that stores calibration constants of the power sensor. The diode power sensors do not have the dc substitution feature, hence it is necessary to provide a reference RF power source for calibration purposes. More information on RF and microwave power sensors and

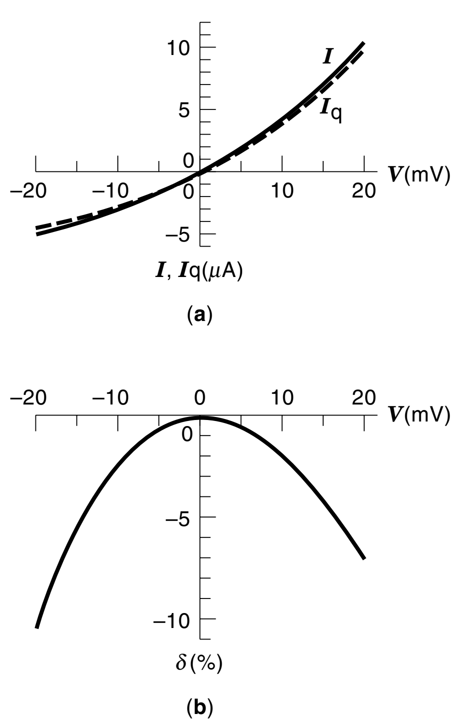



**Figure 20.** $I$–$V$ characteristic of a diode power sensor, (a) $I$–$V$ characteristic of a Schottky diode, (b) error of the square-law relationship.

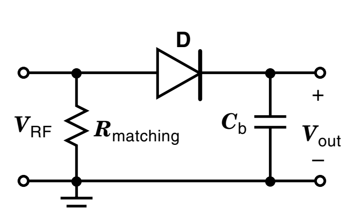



**Figure 21.** HF diode power sensor.

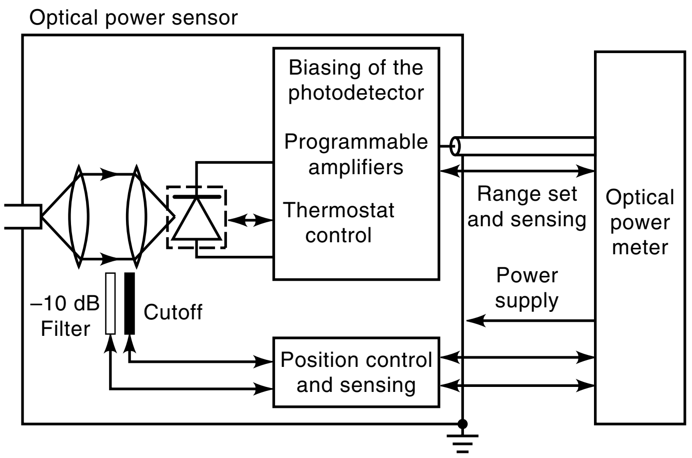



**Figure 22.** Optical power sensor and optical power meter. An optical power meter and optical power sensor create an optical power measurement system. The optical power meter works with a set of dedicated optical power sensors.

power meters may be found in Hewlett-Packard Journal papers (18–20).

Uncertainty of a HF power measurement is associated with circuit imperfections of the power sensor and the power meter. Because of the complexity of these circuits, usually main partial uncertainties are specified for a power sensor and for a power meter. It is up to the user of this equipment to decide which partial uncertainties need to be considered for a specific measurement and how the total uncertainty needs to be computed. The total uncertainty may be computed as the worst case uncertainty, root sum of the squares (RSS), or according to the ANSI/NCSL 540Z-2 guide. Typical range of combined uncertainty of power sensors is from 3% to 8%, and the range of combined instrumentation uncertainty is from 1% to 5%.

## Optical Power Sensors and Optical Power Meters

A simplified block diagram of an optical power sensor and its connection to an optical power meter is shown in Fig. 22. In the optical power sensor, the optical power, $P_O$, of the measured lightwave is converted to an electrical current, $I_D$, following to the relationship

$$I_D = r_D(\lambda)P_O \tag{36}$$

where $r_D(\lambda)$ is the conversion factor or responsitivity, that is, a function of wavelength, $\lambda$. The output current of the photodetector is very small and needs to be significantly amplified and conditioned before the result of the measurement may be displayed. It is necessary to place a suitable preamplifier (usually two preamplifiers must be used in order to cover the entire dynamic range) in the enclosure of the optical power sensor. One of these preamplifiers has smaller gain but wide bandwidth, while the other has large gain and therefore must have small bandwidth. Depending on measured optical signal level and specific kind of power (average optical power, peak optical modulation power), the control system of the optical power meter chooses the proper preamplifier, its gain and bandwidth. In order to keep the photodetector at a constant temperature, the detector is placed in a thermostat (both heating and cooling techniques are used). If a chopper amplifier is used in an optical power meter, then an optical chopper is used. Disadvantages of optical choppers include reduced bandwidth, slow sampling rate, and possible reflection effects from the chopper. If a dc amplifier is used, constant temperature of the amplifier needs to be secured too. The lightwave may be completely cut off from the optical-to-electrical transducer, which is necessary for zeroing the measurement system. Dynamic range of the optical power meter increases with the use of a reference optical attenuator that may be inserted across the light ray. Typical attenuation of the optical attenuator is −10 dB. Optical power meters cover power ranges from +27 to −110 dBm, with total uncertainty range from 2.5% to 5%, and operate in the wavelength range of 400 nm to 1750 nm (contingent to use of a set of optical power sensors). More characteristics of optical power meters may be found in catalogs of Hewlett-Packard company (14,21), and Tektronix company (15). There are ordinary optical power meters, typically in the form of hand-held instruments, or lightwave multimeters that include a power measurement mode of operation. Measurements may be made in lightwave systems that implement lasers or light-emitting diodes (LED). Optical power meters are used to make measurements of absolute power of active components such as lasers or LEDs, insertion losses, and reflections in optical systems. Relative power measurements (with two-channel optical power meters or in single-channel optical power meters related to a specific measurement result) are also possible. Typically the average value of optical signals is measured, but other measurements, like peak power (high and low levels) over a large bandwidth from dc to 250 MHz, are also offered. Optical power meters are broad-band receivers, integrating power levels over the wavelength specific for the optical power sensor that is applied. For optical component characterization at specific wavelength, a selective wavelength source must be used. Typical photodetectors used in optical power meters include large-area photodiodes, thermopiles, and pyroelectric crystals. To cover the entire fiber optic wavelength range, three semiconductor materials are used to make photodetectors. Silicon detectors operate in the range from 400 nm to 1020 nm, germanium detectors cover the range from 900 nm to 1650 nm, and indium gallium arsenide (InGaAs) detectors handle the range from 800 nm to 1700 nm. Detectors made of these materials have some characteristics superior over the other two materials, hence selection of the best detector for a given application is essential. A broad description of topics related to optical power meters may be found in Hewlett-Packard publications (22–27) and in Derickson's book (28).

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**POWER METERS.** See WATTMETERS.

**POWER PLANT DESIGN.** See STEAM TURBINES.

**POWER PLANT EMISSIONS.** See AIR POLLUTION CONTROL.

**POWER PLANTS.** See FUEL CELL POWER PLANTS; MAGNETOHYDRODYNAMIC POWER PLANTS; WASTE-TO-ENERGY POWER PLANTS; WIND POWER; WIND POWER PLANTS.

**POWER PLANTS, MHD.** See MAGNETOHYDRODYNAMIC POWER PLANTS.