CHAPTER 3

Alternating-Current Meters

3-1 Instructional Objectives

This chapter discusses the characteristics of the different types of meter movements used to measure alternating current (ac). The advantages, limitations, and applications of the various movements are emphasized. After completing the chapter you should be able to

1. List the four principal meter movements discussed in the chapter and an application for each.
2. Describe the purpose and operation of the diode in a half-wave rectifier circuit.
3. Trace the current path in a full-wave bridge rectifier.
4. Describe the purpose of the second diode in a three-lead instrument rectifier.
5. Describe the purpose of the shunt resistor, which is often used in rectifier circuits.
6. List five applications for the electrodynamometer movement.
7. List one disadvantage of the electrodynamometer movement for voltage measurements compared to the d'Arsonval meter movement.
8. List the typical frequency range of the iron-vane meter movement.
9. Calculate ac sensitivity and the value of multiplier resistors for half-wave and full-wave rectification.

2 INTRODUCTION

Several types of meter movements may be used to measure alternating current or voltage. The five principal meter movements used in ac instruments are listed in Table 3-1.

Although there are particular applications for which each type of meter movement in Table 3-1 is best suited, the d'Arsonval meter movement is by

TABLE 3-1
Application of Meter Movements

Meter Movement	Dc Use	Ac Use	Applications
Electrodynamometer	Yes	Yes	"Standards" meter, transfer instrument, wattmeter, frequency meter
Iron-vane	Yes	Yes	"Indicator" applications such as in automobiles
Electrostatic	Yes	Yes	Measurement of high voltage when very little current can be supplied by the circuit being measured
Thermocouple	Yes	Yes	Measurement of radio-frequency ac signals
d'Arsonval (PMMC)	Yes	Yes—with rectifiers	Most widely used meter movement for measuring direct current or voltage and resistance

far the most frequently used, even though it cannot directly measure alternating current or voltage. Therefore, we begin with a discussion of instruments for measuring alternating signals that use the d'Arsonval meter movement.

3-3 D'ARSONVAL METER MOVEMENT USED WITH HALF-WAVE RECTIFICATION

In Chapter 2 we discussed the measurement of direct current and voltage, as well as resistance measurements, using the d'Arsonval meter movement which is a dc-responding device. In this chapter we will discover that we can use the same d'Arsonval meter movement to measure alternating current and voltage.

In order to measure alternating current with the d'Arsonval meter movement, we must first **rectify** the alternating current by use of a **diode** rectifier to produce unidirectional current flow. Several types of rectifiers are selected, such as a copper oxide rectifier, a vacuum diode, or a semiconductor or "crystal" diode.

If we add a diode to the dc voltmeter circuit discussed in Chapter 2, as shown in Fig. 3-1, we will have a circuit that is capable of measuring ac voltage.

Recall from Chapter 2 that the sensitivity of a dc voltmeter is

$$S = \frac{1}{I_{fs}} = \frac{1}{1\text{ mA}} = 1\text{ k}\Omega/\text{V} \tag{2-8}$$

A multiplier of ten times this value means a 10-V dc input will cause exactly full-scale deflection when connected with the polarity indicated in

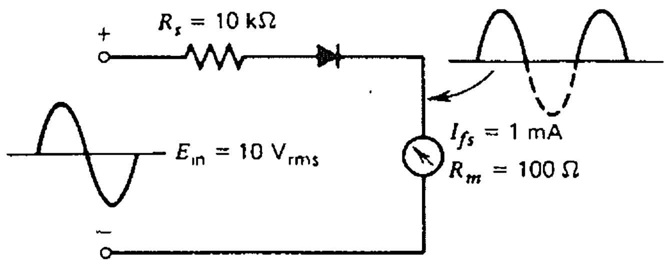

FIGURE 3-1 Dc voltmeter circuit modified to measure ac voltage.

Fig. 3-1. The forward-biased diode will have no effect on the operation of the circuit if we assume an ideal diode.

Now suppose we replace the 10-V dc input with a 10-V **rms (root-mean-square)** sine-wave input. The voltage across the meter movement is just the positive half-cycle of the sine wave because of the rectifying action of the diode. The peak value of the 10-V rms sine wave is

$$E_p = 10\ V_{rms} \times 1.414 = 14.14\ V_{peak} \qquad (3\text{-}1)$$

The dc meter movement will respond to the **average** value of the ac sine wave where the average, or dc value, is equal to 0.318 times the peak value, or

$$E_{ave} = E_{dc} = 0.318 \times E_p$$

This is sometimes written as

$$E_{ave} = \frac{E_p}{\pi} = 0.45 \times E_{rms}$$

The diode action produces an approximate half sine wave across the load resistor. The average value of this voltage is referred to as the dc voltage. This is the voltage to which a dc voltmeter connected across the load resistor would respond. For example, if the output voltage from a half-wave rectifier is 10 V, a dc voltmeter will provide an indication of approximately 4.5 V. Therefore, we can see that the pointer that deflected full scale when a 10-V dc signal was applied deflects to only 4.5 V when we apply a 10-V rms **sinusoidal** ac waveform. This means that the ac voltmeter is not as sensitive as the dc voltmeter. In fact, an ac voltmeter using half-wave rectification is only *approximately* 45% as sensitive as a dc voltmeter.

Actually, the circuit would probably be designed for full-scale deflection with a 10-V rms alternating current applied, which means the multiplier resistor would be only 45% of the value of the multiplier resistor for a 10-V dc voltmeter. Since we have seen that the equivalent dc voltage is equal to 45% of the rms value of the ac voltage, we can express this in the form of an equation for computing the value of the multiplier resistor,

$$R_s = \frac{E_{dc}}{I_{dc}} - R_m = \frac{0.45 E_{rms}}{I_{dc}} - R_m \qquad (3\text{-}2)$$

We can infer from Eq. 3-2, for a half-wave rectifier, that

$$S_{ac} = 0.45 S_{dc} \tag{3-3a}$$

EXAMPLE 3-1

Compute the value of the multiplier resistor for a 10-V rms ac range on the voltmeter shown in Fig. 3-2 using

(a) Equation 2-8.
(b) Equation 3-3a.
(c) Equation 3-2.

Solution

We can approach the problem in several ways. Consider the following.

(a) We can first find the sensitivity of the meter movement.

$$S_{dc} = \frac{1}{I_{fs}} = \frac{1}{1\text{ mA}} = \frac{1\text{ k}\Omega}{\text{V}}$$

Multiplying the dc sensitivity by the dc range gives us the total resistance, from which we subtract the resistance of the meter movement as

$$R_s = S_{dc} \times \text{Range}_{dc} - R_m$$
$$= \frac{1\text{ k}\Omega}{\text{V}} \times \frac{0.45E_{rms}}{1} - R_m$$
$$= \frac{1\text{ k}\Omega}{\text{V}} \times \frac{4.5\text{ V}}{1} - 300\ \Omega = 4.2\text{ k}\Omega$$

(b) We may also choose to start by finding the ac sensitivity for a half-wave rectifier:

$$S_{ac} = 0.45 S_{dc} = 0.45 \times \frac{1}{I_{fs}} = \frac{450\ \Omega}{\text{V}} \tag{3-3a}$$

Then we can say

$$R_s = S_{ac} \times \text{Range}_{ac} - R_m$$
$$= \frac{450\ \Omega}{\text{V}} \times \frac{10\text{ V}}{1} - 300\ \Omega = 4.2\text{ k}\Omega$$

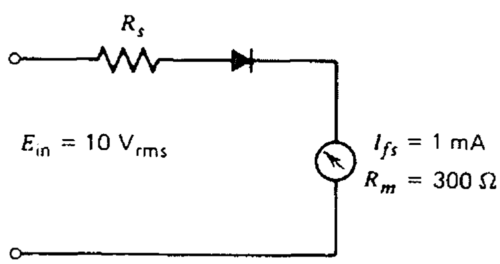

FIGURE 3-2 Ac voltmeter using half-wave rectification.

(c) If we have no interest in the sensitivity, we can use Eq. 3-2:

$$R_s = \frac{0.45E_{rms}}{I_{fs}} - R_m$$

$$= \frac{0.45 \times 10\ V_{rms}}{1\ \text{mA}} - 300\ \Omega$$

$$= \frac{4.5\ \text{V}}{1\ \text{mA}} - 300\ \Omega = 4.2\ \text{k}\Omega \qquad (3\text{-}2)$$

You should note in methods a and b of Example 3-1 that we must be consistent in working with ac or dc parameters. If, as in method a, you wish to work with dc sensitivity, you must work with dc voltage. Similarly, if you work with ac sensitivity, you must work with ac voltage.

Commercially produced ac voltmeters that use half-wave rectification also have an additional diode and a shunt as shown in Fig. 3-3. This double-diode arrangement in a single package is generally called an **instrument rectifier**. The additional diode D_2 is reverse-biased on the positive half-cycle and has virtually no effect on the behavior of the circuit. In the negative half-cycle, D_2 is forward-biased and provides an alternate path for reverse-biased leakage current that would normally flow though the meter movement and diode D_1. The purpose of the shunt resistor R_{sh} is to increase the current flow through D_1 during the positive half-cycle so that the diode is operating in a more linear portion of its characteristic curve.

Although this shunt resistor improves the linearity of the meter on its low-voltage ac ranges, it also further reduces the ac sensitivity.

AMPLE 3-2

In the half-wave rectifier shown in Fig. 3-4, diodes D_1 and D_2 have an average forward resistance of 50 Ω and are assumed to have an infinite resistance in the reverse direction. Calculate the following.

(a) The value of the multiplier R_s.
(b) The ac sensitivity.
(c) The equivalent dc sensitivity.

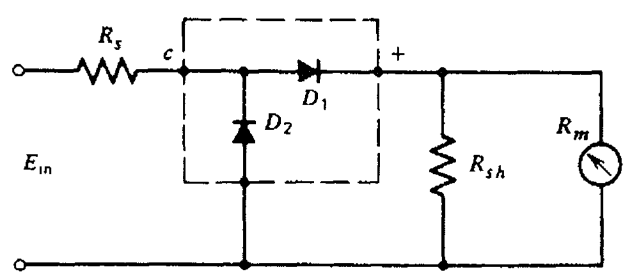

FIGURE 3-3 Half-wave rectification using an instrument rectifier and a shunt resistor for improved linearity.

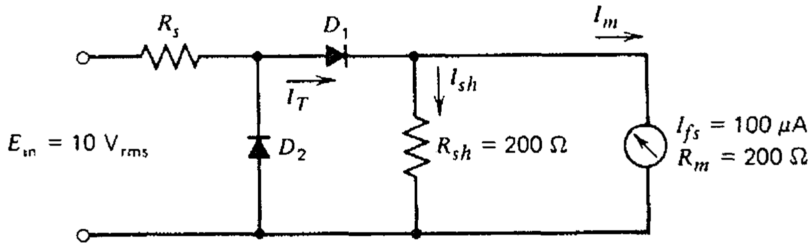

FIGURE 3-4 Half-wave rectifier with shunt resistor.

Solution

(a)

$$I_{sh} = \frac{E_m}{R_{sh}} = \frac{100\ \mu\text{A} \times 200\ \Omega}{200\ \Omega} = 100\ \mu\text{A}$$

$$I_T = I_{sh} + I_m = 100\ \mu\text{A} + 100\ \mu\text{A} = 200\ \mu\text{A}$$

$$E_{dc} = 0.45 \times E_{\text{rms}} = 0.45 \times 10\ \text{V} = 4.5\ \text{V}$$

The total resistance of the meter circuit is

$$R_T = \frac{E_{\text{dc}}}{I_T} = \frac{4.5\ \text{V}}{200\ \mu\text{A}} = 22.5\ \text{k}\Omega$$

The total resistance is made up of several separate resistances and is computed as

$$R_T = R_s + R_d + \frac{R_m R_{sh}}{R_m + R_{sh}}$$

Therefore, we can solve for R_s as

$$R_s = R_T - R_d - \frac{R_m R_{sh}}{R_m + R_{sh}}$$

$$= 22{,}500\ \Omega - 50\ \Omega - \frac{200\ \Omega \times 200\ \Omega}{200\ \Omega + 200\ \Omega}$$

$$= 22.35\ \text{k}\Omega$$

(b) The ac sensitivity is computed as

$$S_{\text{ac}} = \frac{R_T}{\text{Range}} = \frac{22{,}500\ \Omega}{10\ \text{V}} = 2250\ \Omega/\text{V}$$

(c) The dc sensitivity is computed as

$$S_{\text{dc}} = \frac{1}{I_T} = \frac{1}{200\ \mu\text{A}} = 5000\ \mu/\text{V}$$

or alternatively as

$$S_{dc} = \frac{S_{ac}}{0.45} = \frac{2250\ \Omega/V}{0.45} = 5000\ \Omega V$$

XAMPLE 3-3

Using the $E-I$ curve, you can determine the diode in the circuit in Fig. 3-5 to have 1-kΩ static resistance with full-scale deflection current of 100 μA through it. Compute the value of the multiplier resistor using the value R_d at full-scale deflection. Compute the diode resistance with 20-μA current and the value of input voltage that would cause 20 μA to flow.

olution

The value of the multiplier resistor is found as

$$R_s = \frac{0.45E_{rms}}{I_{dc}} - (R_m + R_d) = 4.5\ k\Omega - 1.2\ k\Omega = 3.3\ k\Omega \qquad (3\text{-}2)$$

The static resistance of the diode at 20 μA is

$$R_d = \frac{E_d}{I_d} = \frac{0.04\ V}{20\ \mu A} = 2\ k\Omega$$

The total resistance of the circuit is now

$$R_T = R_s + R_d + R_m$$
$$= 3.3\ k\Omega + 2\ k\Omega + 0.2\ k\Omega$$

The dc voltage that will cause 20 μA is

$$E_{dc} = I_{dc} \times R_T$$
$$= 20\ \mu A \times 5.5\ k\Omega = 0.11\ V$$

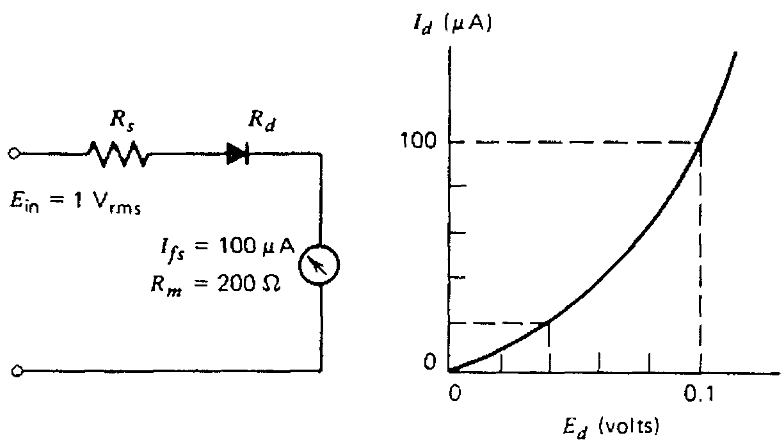

FIGURE 3-5 Circuit and $E-I$ curve for Example 3-3.

The input voltage that will cause 20 μA is

$$E_{in} = \frac{E_{dc}}{0.45} = \frac{0.11}{0.45} = 0.23\ V_{rms}$$

If the diode resistance had not changed, the input voltage that would cause a 20-μA current to flow would be equal to 0.09 V. Therefore, an error of approximately 22% now exists.

3-4 D'ARSONVAL METER MOVEMENT USED WITH FULL-WAVE RECTIFICATION

Frequently, it is more desirable to use a full-wave rather than a half-wave rectifier in ac voltmeters because of the higher sensitivity rating. The most frequently used circuit for full-wave rectification is the bridge-type rectifier shown in Fig. 3-6.

During the positive half-cycle, current flows through diode D_2, through the meter movement from positive to negative, and through diode D_3. The polarities in circles on the transformer secondary are for the positive half-cycle. Since current flows through the meter movement on both half-cycles, we can expect the deflection of the pointer to be greater than with the half-wave rectifier, which allows current to flow only on every other half-cycle; if the deflection remains the same, the instrument using full-wave rectification will have a greater sensitivity.

Consider the circuit shown in Fig. 3-7. The peak value of the 10-V rms signal is computed as with the half-wave rectifier as

$$E_p = 1.414 \times E_{rms} = 14.14\ V_{peak}$$

The average, or dc, value of the pulsating sine wave is

$$E_{ave} = 0.636 E_p = 9\ V$$

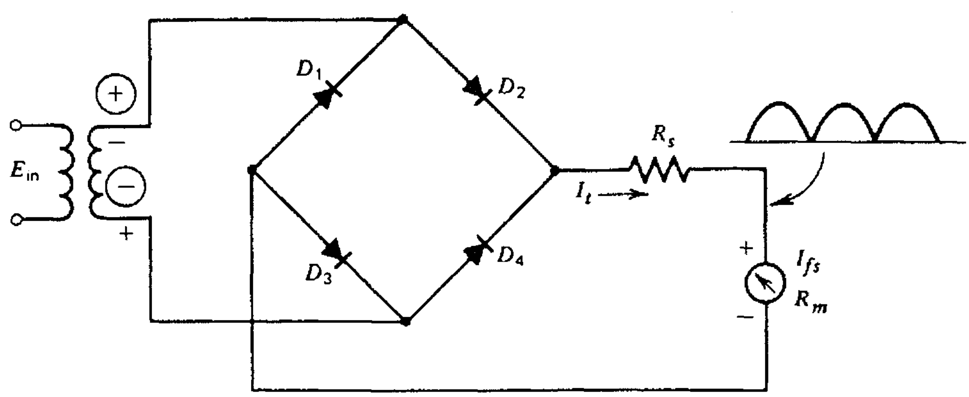

FIGURE 3-6 Full-wave bridge rectifier used in an ac voltmeter circuit.

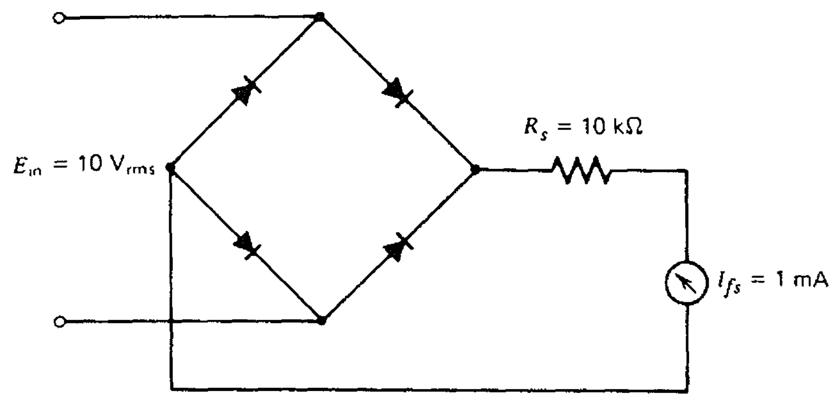

FIGURE 3-7 Ac voltmeter circuit using full-wave rectification.

Alternatively, this can be computed as

$$E_{ave} = 0.9 \times E_{rms} = 0.9 \times 10\ \text{V} = 9\ \text{V}$$

Therefore, we can see that the 10-V rms voltage is equivalent to 9 V_{dc}. When full-wave rectification is used, the pointer will deflect to 90% of full scale. This means an ac voltmeter using full-wave rectification has a sensitivity equal to 90% of the dc sensitivity, or it has twice the sensitivity of a circuit using half-wave rectification. As with the half-wave rectifier, the circuit would be designed for full-scale deflection, which means the value of the multiplier resistor would be only 90% of the value for a 10-V dc voltmeter. We may write this for a full-wave rectifier as

$$S_{ac} = 0.9 S_{dc} \tag{3-3b}$$

MPLE 3-4 Compute the value of the multiplier resistor for a 10-V rms ac range on the voltmeter in Fig. 3-8.

tion The dc sensitivity is

$$S_{dc} = \frac{1}{I_{fs}} = \frac{1}{1\ \text{mA}} = \frac{1\ \text{k}\Omega}{\text{V}} \tag{2-8}$$

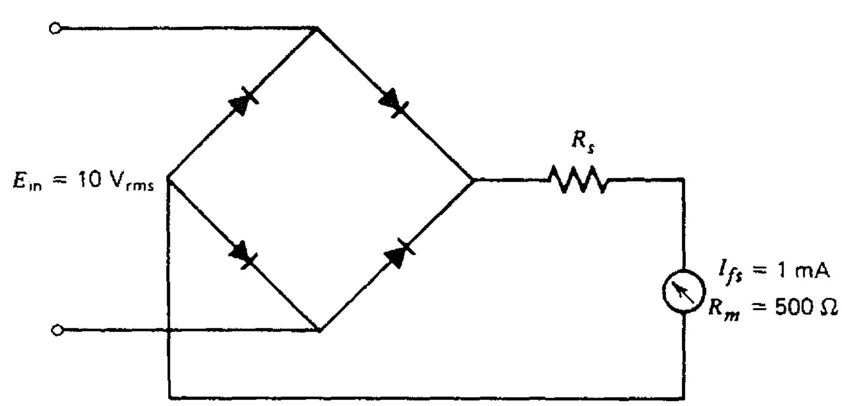

FIGURE 3-8 Ac voltmeter circuit using full-wave rectification.

The ac sensitivity is 90% of the dc sensitivity:

$$S_{ac} = 0.9S_{dc} = 0.9 \times \frac{1\ \text{k}\Omega}{\text{V}} = \frac{900\ \Omega}{\text{V}} \tag{3-3b}$$

The multiplier resistor is therefore found to equal

$$R_s = S_{ac} \times \text{Range} - R_m$$
$$= \frac{900\ \Omega}{\text{V}} \times 10\ V_{rms} - 500\ \Omega = 8.5\ \text{k}\Omega$$

EXAMPLE 3-5

Each diode in the full-wave rectifier circuit shown in Fig. 3-9 has an average forward resistance of 50 Ω and is assumed to have an infinite resistance in the reverse direction. Calculate the following.

(a) The value of the multiplier R_s.

(b) The ac sensitivity.

(c) The equivalent dc sensitivity.

Solution

(a) We begin by computing the shunt current and the total current,

$$I_{sh} = \frac{E_m}{R_{sh}} = \frac{1\ \text{mA} \times 500\ \Omega}{500\ \Omega} = 1\ \text{mA}$$

and

$$I_T = I_{sh} + I_m = 1\ \text{mA} + 1\ \text{mA} = 2\ \text{mA}$$

The equivalent dc voltage is computed as

$$E_{dc} = 0.9 \times 10\ V_{rms} = 0.9 \times 10\ \text{V} = 9.0\ \text{V}$$

The total resistance of the meter circuit can now be computed as

$$R_T = \frac{E_{dc}}{I_T} = \frac{9.0\ \text{V}}{2\ \text{mA}} = 4.5\ \text{k}\Omega$$

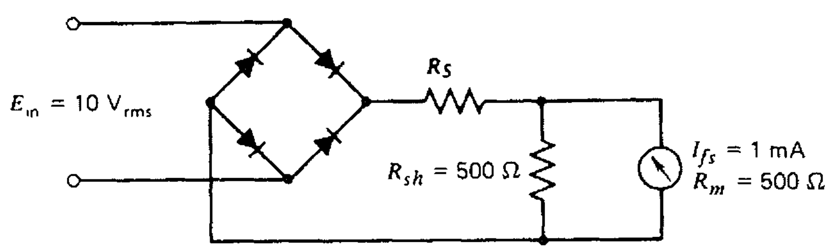

FIGURE 3-9 Ac voltmeter circuit using full-wave rectification and shunt.

and

$$R_s = R_T + 2R_d - \frac{R_m R_{sh}}{R_m + R_{sh}}$$

$$= 4500\ \Omega + 2 \times 50\ \Omega - \frac{500\ \Omega \times 500\ \Omega}{500\ \Omega + 500\ \Omega} = 4.15\ \text{k}\Omega$$

(b) The ac sensitivity is computed as

$$S_{ac} = \frac{R_T}{\text{Range}} = \frac{4500\ \Omega}{10\ \text{V}} = 450\ \Omega/\text{V}$$

(c) The dc sensitivity is computed as

$$S_{dc} = \frac{1}{I_T} = \frac{1}{2\ \text{mA}} = 500\ \Omega/\text{V}$$

or alternatively as

$$S_{dc} = \frac{S_{ac}}{0.9} = \frac{450\ \Omega\text{V}}{0.9} = 500\ \Omega/\text{V}$$

Take note that voltmeters using half-wave or full-wave rectification are suitable for measuring only sinusoidal ac voltages. In addition, the equations presented thus far are *not* valid for nonsinusoidal waveforms such as square, triangular, and sawtooth waves.

ELECTRODYNAMOMETER MOVEMENT

The **electrodynamometer movement** is the most fundamental meter movement in use today. Like the d'Arsonval movement previously discussed,' the electrodynamometer is a current-sensitive device. That is, the pointer deflects up scale because of current flow through a moving coil. Even though this meter movement is the most fundamental in use, it is also the most versatile. Singe-coil movements may be used to measure direct or alternating current or voltage, or in a single-phase wattmeter or varmeter. Double-coil movements may be used in polyphase wattmeter or varmeter, and crossed-coil movements may be used as a power factor meter or as a frequency meter. Aside from all this, perhaps the most important applications for electrodynamometer movements are as voltmeter and ammeter **standards** and **transfer** instruments. Because of the inherent accuracy of the electrodynamometer movement, it lends itself well to use in **standards instruments**, those used for the calibration of other meters. The term **transfer instrument** is applied to an instrument that may be calibrated with a dc source and then used

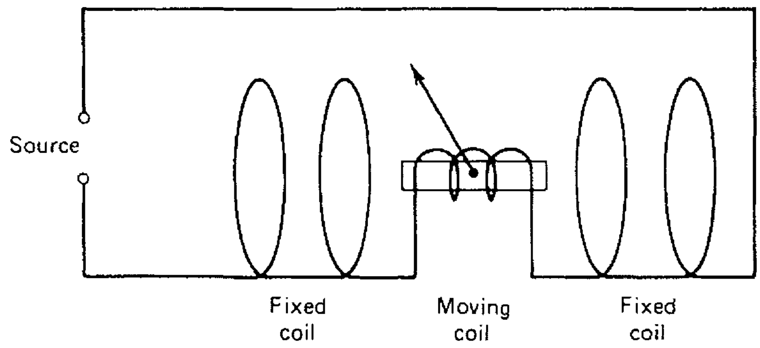

FIGURE 3-10 Electrodynamometer movement.

without modification to measure alternating current. This gives us a direct means of equating ac and dc measurements of voltage and current.[1]

The single-coil electrodynamometer movement consists of a fixed coil, divided into two equal halves, separated by a movable coil, as shown in Fig. 3-10. Both halves of the split fixed coil and the moving coil are connected in series, and current from the circuit being measured passes through all the coils causing a magnetic field around the fixed coils. The movable coil rotates in this magnetic field.

The basic electrodynamometer movement is capable of handling much more current than a d'Arsonval movement could handle without a shunt. A current flow of 100 mA is an approximate value for the maximum current without a shunt resistance. The increased current-handling capabilities are a direct result of the basic design of the meter movement. The magnetic coupling between the fixed coils and the moving coils is across an air gap that results in a weak magnetic field. For magnetic coupling to be sufficient, more current must flow through the coils, which means that a larger-diameter wire must be used. However, the larger-diameter wire has less resistance than a smaller-diameter wire. This causes the electrodynamometer movement to have a very *low* sensitivity rating of approximately 20 to 100 Ω/V.

EXAMPLE 3-6

An electrodynamometer movement that has a full-scale deflection current rating of 10 mA is to be used in a voltmeter circuit. Calculate the value of the multiplier for a 10-V range if R_m equals 50 Ω.

Solution

The sensitivity of the meter movement is

$$S = \frac{1}{I_{fs}} = \frac{1}{10\text{ mA}} = \frac{100\ \Omega}{\text{V}} \tag{2-8}$$

Therefore, the value of the multiplier resistor is

$$R_s = S \times \text{Range} - R_m$$

$$= \frac{100\ \Omega}{\text{V}} \times 10\text{ V} - 50\ \Omega = 950\ \Omega \tag{2-9}$$

[1]There is a frequency limitation to ac use, however. Most electrodynamometer movements are accurate over the frequency range from 0 to 125 Hz.

This resistor is placed in series with the meter movement in the same way as with the d'Arsonval meter movement.

When a shunt resistor is used with an electrodynamometer movement to expand current-measuring capabilities, the shunt resistor is normally placed in parallel with only the moving coil, as shown in Fig. 3-11. Since only the moving coil is shunted, the resistance of the moving coil would have to be known in order to compute the value of the shunt.

F_E 3-7

An electrodynamometer movement with a full-scale deflection current rating of 10 mA is to be used as a 1-A ammeter. If the resistance of the moving coil is 40 Ω, what is the value of the shunt?

on

The value of the shunt is computed in the same manner as discussed when using the d'Arsonval meter movement.

$$R_{sh} = \frac{R_m}{n-1}$$

$$= \frac{40\ \Omega}{100-1} = \frac{40\ \Omega}{99} = 0.404\ \Omega \qquad (2\text{-}3)$$

If the ammeter in Example 3-7 is connected to a 1-A dc source, the meter pointer should deflect to exactly full scale. The pointer should also deflect full scale if the 1-A dc source is replaced with a 1-A rms ac source.

Since the same current flows through the field coils and the moving coil, when the electrodynamometer movement is used as either an ammeter or a voltmeter, the pointer deflects as the square of the current. The result is a **square-law meter scale** such as is shown in Fig. 3-12.

Probably the most extensive application of the electrodynamometer movement is in wattmeters. The wattmeter may be used to measure either ac or dc power. The ac signals are not restricted to sinusoidal waveforms so that power developed by any ac waveform may be measured. When used as a wattmeter, the electrodynamometer is connected as shown in Fig. 3-13.

When used as a wattmeter, the fixed coils, called 'field' coils, are in series with the load and therefore conduct the same current as the load (plus a small current through the moving coil). The moving coil is connected as a

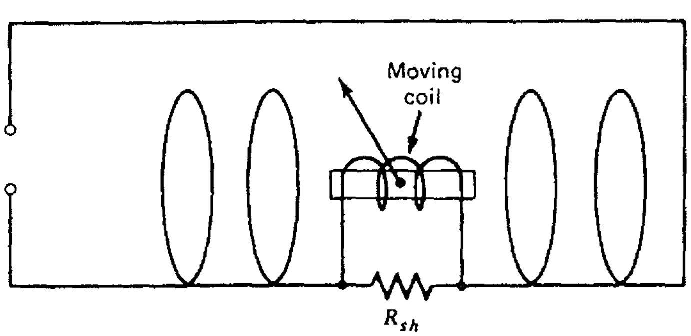

FIGURE 3-11 Electrodynamometer movement used as an ammeter.

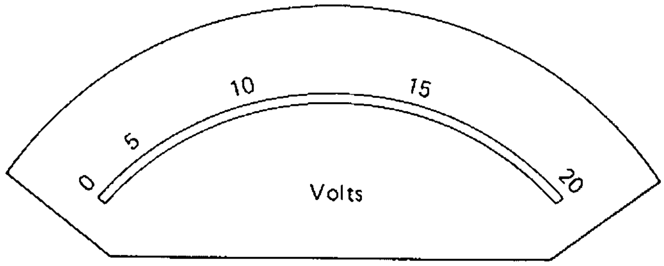

FIGURE 3-12 Square-law meter scale.

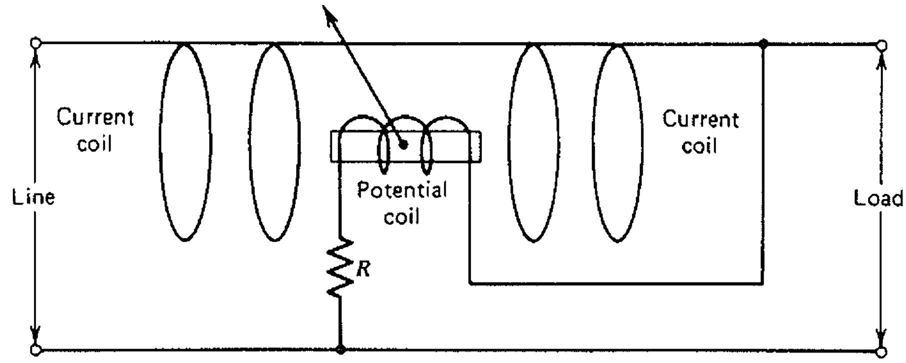

FIGURE 3-13 Electrodynamometer movement used as a wattmeter.

voltmeter across the load where the resistor R_s is the multiplier for the voltage-sensitive meter. The magnetic torque that causes the pointer to deflect up scale can be expressed in terms of the amount of deflection as

$$\theta_m = K_m EI \cos\theta \tag{3-4}$$

where

θ_m = angular deflection of the pointer
K_m = instrument constant, degrees per watt
E = rms value of source voltage
I = rms value of source current
$\cos\theta$ = power factor

EXAMPLE 3-8

A wattmeter that uses an electrodynamometer movement with $K_m = 8°/\text{W}$ is used to measure the power dissipated in an ac circuit. If the applied voltage of 100 V_{rms} produces a current of 0.5 A with a power factor of 0.8, how many degrees does the meter pointer deflect?

Solution

The angular deflection of the pointer may be calculated using

$$\theta_m = K_m EI \cos\theta$$

$$= \frac{8°}{\text{W}} \times \frac{110\text{ V}}{1} \times \frac{0.05\text{ A}}{1} \times \frac{0.8}{1} = 35.2° \tag{3-4}$$

Since volts times amperes equals watts, all units divide out except degrees, which are the correct units for angular deflection.

3-6 IRON-VANE METER MOVEMENT

The **iron-vane meter movement**, which consists of a fixed coil of many turns and two iron vanes placed inside the fixed coil, is widely used in industry for applications in which ruggedness is more important than a high degree of accuracy.

The current to be measured passes through the windings of the fixed coil, setting up a magnetic field that magnetizes the two iron vanes with the same polarity. This causes the iron vanes to repel one another. If one of the iron vanes is attached to the frame of a fixed coil, the other iron vane will then be repelled by an amount related to the square of the current. Therefore, the square-law meter scale shown in Fig. 3-12 is used with the basic iron-vane meter movement as well as with the electrodynamometer movement.

The basic iron-vane movement has a square-law response, but the fixed coil can be designed to provide a relatively linear response. The radial-vane design shown in Fig. 3-14 is just such a variation and does in fact have a nearly linear scale.

Although the iron-vane movement is responsive to direct current, the hysteresis, or magnetic lag, in the iron vanes causes appreciable error. Therefore, moving-vane instruments for measuring direct current are rarely used except for very inexpensive indicators, such as charge-discharge indicators on automobiles.

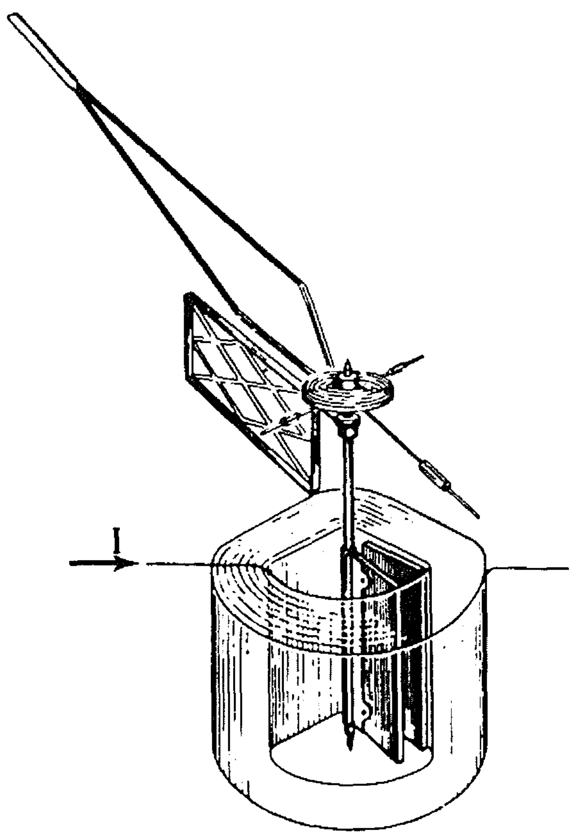

FIGURE 3-14 Radial-type iron-vane movement. (Courtesy Weston Instruments, a Division of Sangamo Weston, Inc.)

For ac applications, the magnetic lag presents no problems. Therefore, iron-vane meter movements are used extensively in industry for measuring alternating current when errors on the order of 5% to 10% are acceptable.

The basic current responding iron-vane meter movement can be used to measure voltage by adding a multiplier resistor as with the d'Arsonval movement. However, the iron-vane movement is very sensitive to frequency change and can be expected to provide accurate readings over a limited frequency range, approximately 25 to 125 Hz. When accurate measurements at higher frequencies are required, the thermocouple meter (see Section 3-7) is used. The iron-vane movement is sensitive to frequency primarily because the magnetization of the iron vane is nonlinear and because of losses incurred by eddy currents and hysteresis.

3-7 THERMOCOUPLE METER

A basic **thermocouple meter** is an instrument that consists of a heater element, usually made of fine wire, a thermocouple, and a d'Arsonval meter movement. This instrument can be used to measure both alternating current and direct current. The most attractive characteristic of the thermocouple meter is that it can be used to measure very high-frequency alternating currents. In fact, such instruments are very accurate well above 50 MHz. The schematic for a very basic thermocouple meter is shown in Fig. 3-15.

The instrument derives its name from the fact that its operation is based on the action of a thermocouple. A thermocouple, which consists of two dissimilar metals, develops a very small potential difference (0 to 10 mV) at the junction of the two metals. This potential difference, which is a function of the junction temperature, causes current to flow through the meter movement.

The thermocouple senses the temperature of the heater wire, which is a function of the current or the voltage being measured. Therefore, the thermocouple and the heater must be thermally coupled but electrically isolated.

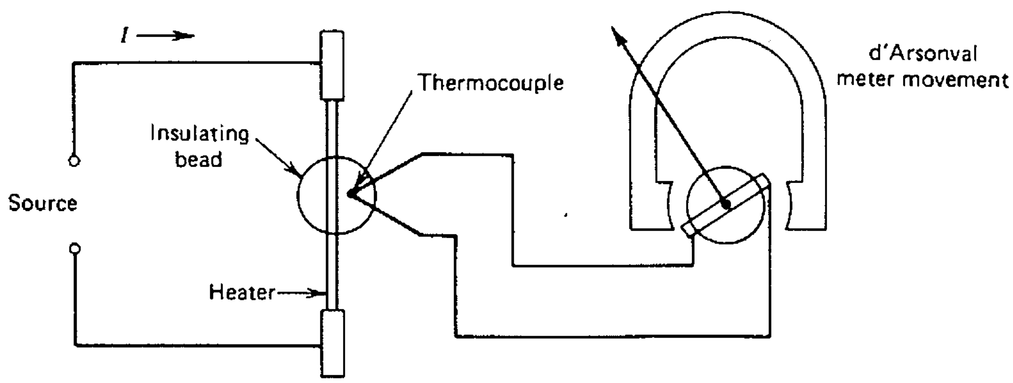

FIGURE 3-15 Schematic for a basic thermocouple meter.

Instruments for measuring over a wide range of currents (approximately 1 to 50 mA) are available. The following example illustrates the calculations involved in designing a basic three-range thermocouple voltmeter.

EXAMPLE 3-9

Design a basic three-range (5, 10, 25 V) thermocouple voltmeter around the following specifications.

- d'Arsonval meter movement:

$$I_{fs} = 50\ \mu A$$

$$R_m = 200\ \Omega$$

- Heater:

$$I_{max} = 5\ mA$$

$$R = 200\ \Omega$$

- Thermocouple: Thermocouple related specifications are shown in Figures 3-16 and 3-17.

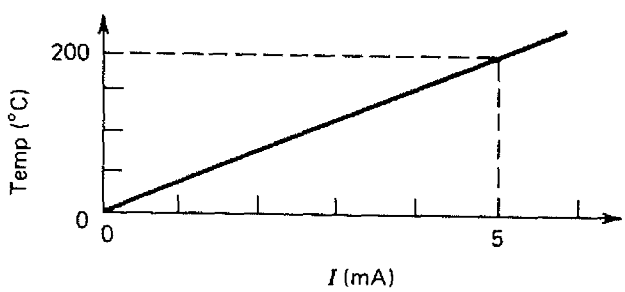

FIGURE 3-16 Heater current versus temperature graph.

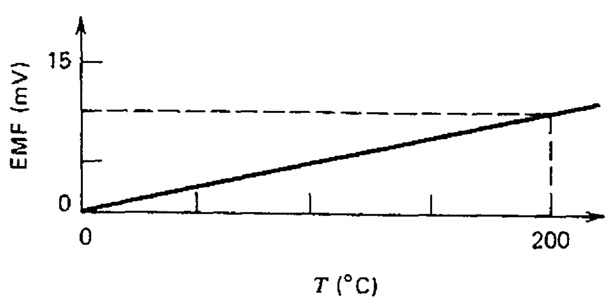

FIGURE 3-17 Graph of thermocouple junction temperature versus potential difference.

Solution

The value of the multiplier on each of the three ranges is calculated as follows.

(a) On the 5-V range,

$$R_s = \frac{E}{I_{max}} - R_n = \frac{5\text{ V}}{5\text{ mA}} - 200\ \Omega = 1\text{ k}\Omega - 200\ \Omega = 800\ \Omega$$

(b) On the 10-V range,

$$R_s = \frac{E}{I_{max}} - R_n = \frac{10\text{ v}}{5\text{ mA}} - 200\ \Omega = 1.8\text{ k}\Omega$$

(c) On the 25-V range,

$$R_s = \frac{E}{I_{max}} - R_n = \frac{25\text{ V}}{5\text{ mA}} - 200\ \Omega = 4.8\text{ k}\Omega$$

The graph of heater current versus temperature (Fig. 3-16) shows that the thermocouple temperature will be 200°C when the heater current is 5 mA. The graph of thermocouple junction temperature versus potential difference (Fig. 3-17) shows that a potential difference of 10 mV exists when the junction temperature is 200°C. A potential difference of 10 mV at the input terminals of the d'Arsonval meter movement causes full-scale deflection current flow. This is calculated as

$$I = \frac{E}{R_m} = \frac{10\text{ mV}}{200\ \Omega} = 50\ \mu\text{A}$$

The schematic diagram for the circuit is shown in Fig. 3-18.

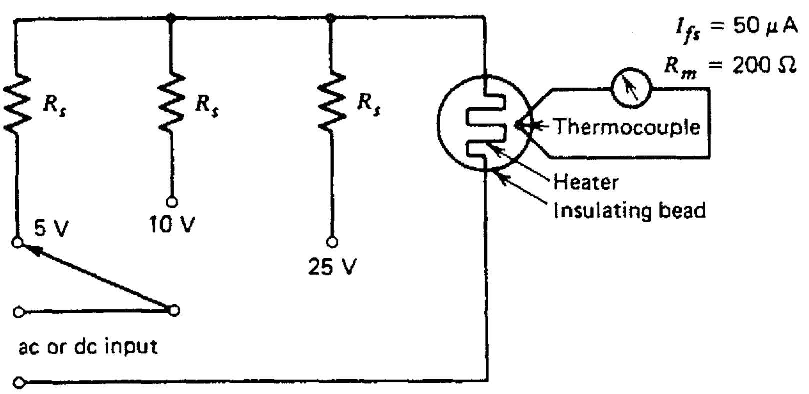

FIGURE 3-18 Multiple-range voltmeter using a thermocouple meter.

3-8 LOADING EFFECTS OF AC VOLTMETERS

As has already been discussed, the sensitivity of ac voltmeters, using either half-wave or full-wave rectification, is less than the sensitivity of dc voltmeters. Therefore, the loading effect of an ac voltmeter is greater than that of a dc voltmeter.

EXAMPLE 3-10

Determine the reading obtained with a dc voltmeter in the circuit in Fig. 3-19 when switch S is set to position A; then set the switch to position B and determine the reading obtained with a half-wave and a full-wave ac voltmeter. All the meters use a 100-μA full-scale deflection meter movement and are set on their 10-V dc or rms ranges.

Solution

The reading obtained with the dc voltmeter is computed as follows.

$$S_{dc} = \frac{1}{I_{fs}} = \frac{1}{100\ \mu\text{A}} = \frac{10\ \text{k}\Omega}{\text{V}} \qquad (2\text{-}8)$$

$$R_s = S_{dc} \times \text{Range}$$

$$= \frac{10\ \text{k}\Omega}{\text{V}} \times \frac{10\ \text{V}}{1} = 100\ \text{k}\Omega \qquad (2\text{-}9)$$

$$E = 20\ \text{V} \times \frac{100\ \text{k}\Omega \| 10\ \text{k}\Omega}{100\ \text{k}\Omega \| 10\ \text{k}\Omega + 10\ \text{k}\Omega}$$

$$= 20\ \text{V} \times \frac{9.09\ \text{k}\Omega}{9.09\ \text{k}\Omega + 10\ \text{k}\Omega} = 9.52\ \text{V}$$

The reading obtained with the ac voltmeter using half-wave rectification is computed as

$$S_{hw} = 0.45 S_{dc} = \frac{4.5\ \text{k}\Omega}{\text{V}} \qquad (3\text{-}3\text{a})$$

$$R_s = S_{hw} \times \text{Range} = 45\ \text{k}\Omega$$

$$E = 20\ \text{V} \times \frac{45\ \text{k}\Omega \| 10\ \text{k}\Omega}{45\ \text{k}\Omega \| 10\ \text{k}\Omega + 10\ \text{k}\Omega}$$

$$= 20\ \text{V} \times \frac{8.18\ \text{k}\Omega}{8.18\ \text{k}\Omega + 10\ \text{k}\Omega} = 9.0\ \text{V}$$

Finally, the reading obtained with the ac voltmeter using full-wave

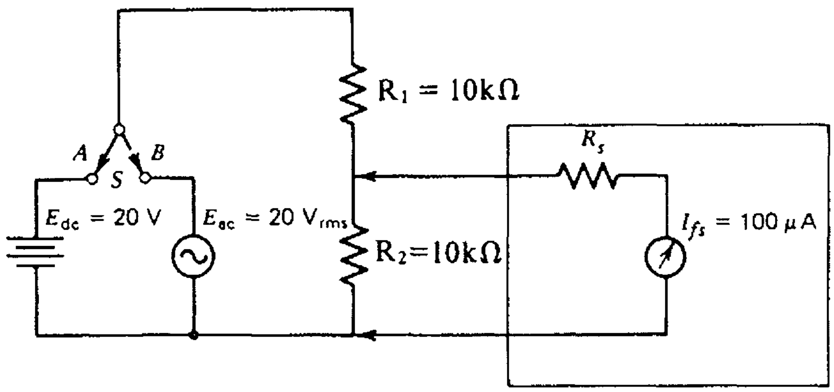

FIGURE 3-19 Circuit for comparing readings of ac and dc voltmeters.

rectification is computed as

$$S_{fw} = 0.90 S_{dc} = \frac{9.0\ \text{k}\Omega}{\text{V}}$$

$$R_s = S_{fw} \times \text{Range} = 90\ \text{k}\Omega$$

$$E = 20\ \text{V} \times \frac{90\ \text{k}\Omega \| 10\ \text{k}\Omega}{90\ \text{k}\Omega \| 10\ \text{k}\Omega + 10\ \text{k}\Omega}$$

$$= 20\ \text{V} \times \frac{9\ \text{k}\Omega}{9\ \text{k}\Omega + 10\ \text{k}\Omega} = 9.47\ \text{V}$$

As can be seen, the ac voltmeter using either half-wave or full-wave rectification has a greater loading effect than the dc voltmeter.

3-9 PEAK-TO-PEAK-READING AC VOLTMETERS

Frequently, it is desirable to measure nonsinusoidal waveforms. One way of taking this measurement is with peak-to-peak-reading ac voltmeters. The block diagram shown in Fig. 3-20 shows a basic peak-to-peak-reading ac voltmeter.

We have already discussed ac voltmeters using either half- or full-wave rectification. Therefore, our interest in this section is with the peak-to-peak detector. A circuit that is capable of detecting the peak-to-peak amplitude of ac signals, either sinusoidal or nonsinusoidal, is shown in Fig. 3-21.

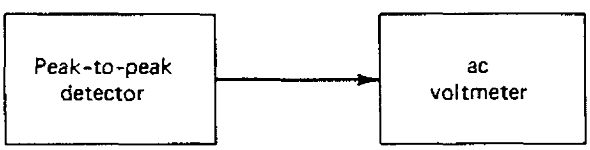

FIGURE 3-20 Block diagram for a peak-to-peak-reading ac voltmeter.

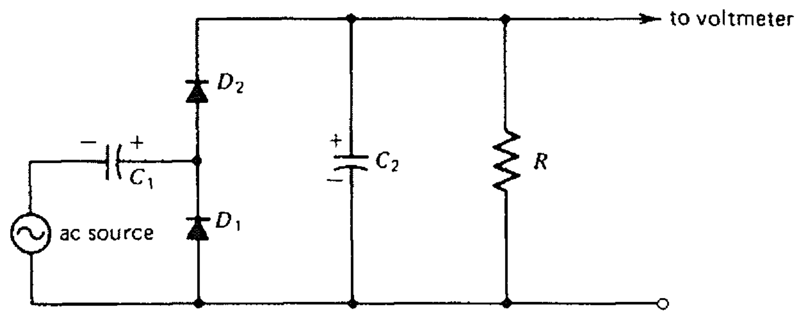

FIGURE 3-21 Peak-to-peak detector.

During the negative half-cycle of the input signal, diode D_1 is forward-biased and charges capacitor C_1 as shown in Fig. 3-21. During the positive half-cycle, diode D_1 is reverse-biased and D_2 is forward-biased. The positive going input signal and the voltage across C_1 are now of the same polarity. Capacitor C_2 charges to the sum of these voltages through D_2. The voltage across C_2 is now equal to the peak-to-peak value of the input signal. This voltage is now applied to an ordinary ac voltmeter. Peak-to-peak reading voltmeters are sometimes used to measure waveforms that either are nonsinusoidal or swing unevenly about a zero reference axis (e.g., 20 V positive and 5 V negative).

APPLICATIONS

Alternative-current voltmeters have many practical applications, both in the laboratory and around the home. One lab application is in transformer testing and in determining whether a waveform is sinusoidal. An ac voltmeter is also very useful around the home. Occasionally, appliances such as refrigerators or air conditioners fail to operate properly because of low ac line voltage. An ac voltmeter can be used to measure the line voltage during "peak" and "slack" demand periods. If the line voltage drops to less than about 100 V during the peak demand period, notify the power company.

To determine whether a waveform is sinusoidal requires a peak-to-peak-reading voltmeter and an rms-responding meter. The peak-to-peak value of the waveform may be obtained regardless of the type of waveform. If the waveform is sinusoidal, the reading obtained with the rms-responding meter will be equal to

$$E_{rms} = \frac{E_{p-p}}{2} \times \frac{0.707}{1} \tag{3-5}$$

Several useful tests on transformers can be performed with an ac voltmeter. Tests to check phase relationships and polarity markings, to check the

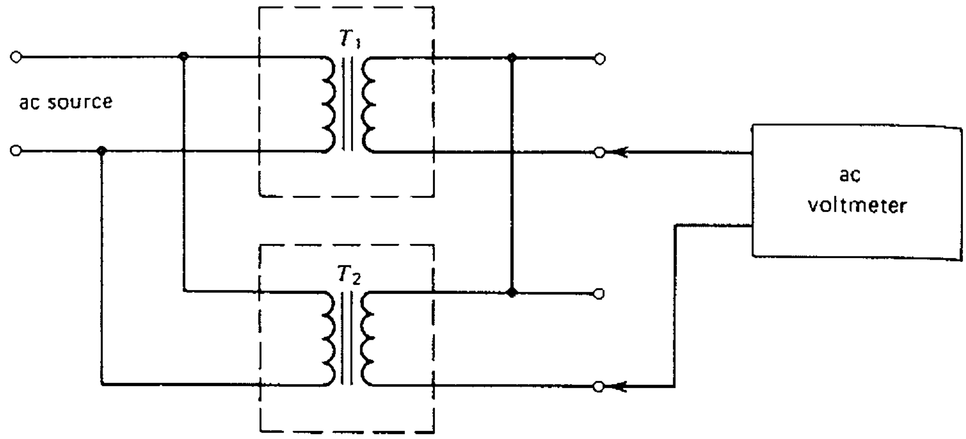

FIGURE 3-22 Test circuit for determining that two transformers are operating in phase.

impedance ratio between the primary and the secondary, to determine the regulating effect of a transformer, or to determine the Q of a tuned transformer are some of the tests that can be performed.

As an example, suppose that two transformers that are supposedly identical are to be operated in parallel and in phase. Many transformers are marked with dots or some similar system to indicate polarity. However, there is no standard system of marking transformers, nor will all transformers be marked in any manner. In such cases the test circuit shown in Fig. 3-22 may be used to check the phase relationship. The transformers are connected in phase if the ac voltmeter reads at, or near, zero. If the voltmeter reading is double the normal transformer secondary voltage for either transformer, the transformers are operating out of phase. The transformers can be made to operate in phase by reversing either the input or the output leads of one transformer. If the voltmeter still indicates a voltage, the transformer secondaries should be separated and the output voltage measured individually. If different secondary voltage readings are obtained, the transformers should not be connected as shown, since the transformers may be damaged.

3-11 SUMMARY

Several different types of meter movements are available for measuring alternating current or voltage. Each type has characteristics that make it most suitable for particular applications. For general purposes the d'Arsonval movement, with either a half-wave or a full-wave rectifier, is widely used.

Table 3-2 is a summary of the responses of the four current-responding meter movements to an ac sine wave or a dc voltage.

TABLE 3-2
Meter Movement Response to Ac or Dc Voltage

Meter Movement	Applied Voltage and Frequency	Reading Obtained
d'Arsonval	10 V_{rms}, 60 Hz	0 V
Iron vane	10 V_{rms}, 60 Hz	10 V
Electrodynamometer	10 V_{rms}, 60 Hz	10 V
Thermocouple	10 V_{rms}, 60 Hz	10 V
d'Arsonval with half-wave rectifier	10 V_{rms}, 60 Hz	4.5 V
d'Arsonval with full-wave rectifier	10 V_{rms}, 60 Hz	9.0 V
Iron vane	10 V_{dc}	10 V
Electrodynamometer	10 V_{dc}	10 V
Thermocouple	10 V_{dc}	10 V

GLOSSARY

Average: The value corresponding to the area under one-half cycle of a sinusoidal waveform divided by the distance of the curve along the horizontal axis.

Diode: An electronic device (usually a semiconductor *p-n* junction) that conducts current readily in only one direction.

Electrodynamometer movement: A basic but versatile meter movement consisting of a fixed coil divided into two equal halves, called field coils, and a moving coil between the field coils.

Electrostatic meter movement: An indicating mechanism resembling a variable capacitor and the only mechanism used for electrical indications that measures voltage directly rather than by the effect of current.

Instrument rectifier: A three-terminal molded package consisting of two diodes. One diode acts as a rectifier while the second diode provides a low-resistance path for leakage current of the rectifying diode.

Iron-vane meter movement: A meter movement in which the movable element in an iron vane is drawn into a magnetic field developed by the current being measured.

Rectify: To convert alternating current to a unidirectional current by removing or inverting the part of the waveform on one side of the zero-amplitude axis.

RMS v: Root-mean-square.

Sinusoidal: Having the form of a sine wave.

Square-law meter scale: The scale required for a meter movement, such as the iron-vane movement, for which the repelling force, and hence the pointer deflection, is proportional to the square of the current.

Standards instrument: An instrument used to calibrate other instruments.

Thermocouple meter: A meter that uses a thermocouple to sense the temperature of an element heated by a radio-frequency signal. The thermocouple emf is then applied to a d'Arsonval meter movement.

Transfer instrument: An instrument that is used to equate ac and dc measurements because it can be calibrated using direct current and then used to measure alternating current directly.

3-13 REVIEW QUESTIONS

The following questions should be answered after a thorough study of the chapter. The purpose of the questions is to check your comprehension of the material.

1. Which type of meter movement is most widely used in ac instruments for current and voltage measurements?
2. Which type of meter movement is most widely used in wattmeters?
3. How does the sensitivity of an ac voltmeter compare to the sensitivity of a dc voltmeter?
4. Define *transfer instrument.*
5. How does the sensitivity of an ac voltmeter using full-wave rectification compare with the sensitivity of one using half-wave rectification?
6. Which type of meter movement is best studied for use as a transfer instrument?
7. Show how the diodes are connected in an instrument rectifier and explain the purpose of each diode.
8. Which ac meter movement naturally has a square-law scale and why?
9. Compare the effects of circuit loading when using an ac voltmeter with half-wave rectification against those when using an ac voltmeter with full-wave rectification.

3-14 PROBLEMS

3-1 The current through a meter movement is 150 μA_{peak}. What is the dc value if the instrument uses half-wave rectification?

3-2 A d'Arsonval meter movement deflects to 0.8 mA. What is the peak value of the alternating current if the instrument uses full-wave rectification?

3-3 A d'Arsonval meter movement with a full-scale deflection current rating of 1 mA and an internal resistance of 500 Ω is to be used in a half-wave rectifier ac voltmeter. Calculate the ac and dc sensitivity and the value of the multiplier resistor for a 30-V rms range.

3-4 A d'Arsonval meter movement with a full-scale deflection current rating of 200 μA and an internal resistance of 500 Ω is to be used in an ac voltmeter using full-wave rectification. Calculate the value of the multiplier resistor for a 50-V peak-to-peak sine-wave range.

3-5 Calculate the ac and dc sensitivity and the value of the multiplier resistor required to limit current to the full-scale deflection current in the circuit shown in Fig. 3-23.

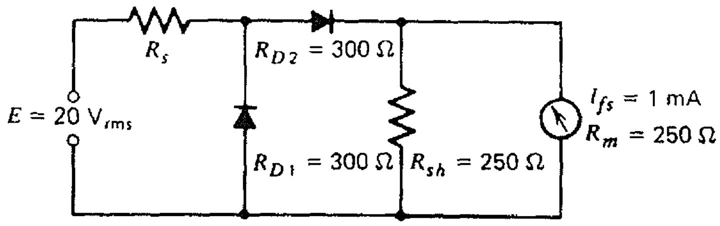

FIGURE 3-23 Circuit for Problem 3-5.

3-6 Calculate the ac and dc sensitivity and the value of the multiplier resistor required to limit current to the full-scale deflection current in the circuit shown in Fig. 3-24. All diodes have a forward resistance of 300 Ω and an infinite reverse resistance.

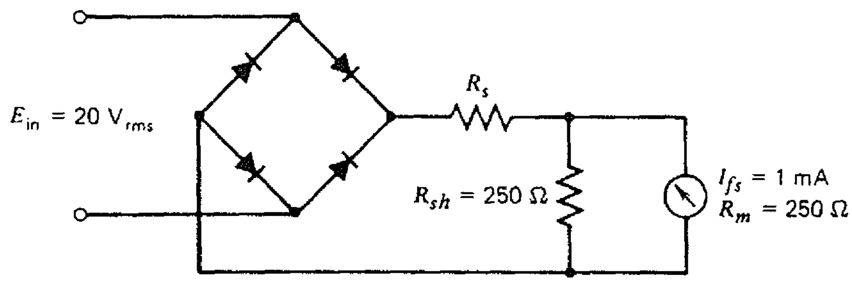

FIGURE 3-24 Circuit for Problem 3-6.

3-7 Figure 3-25 represents a meter face for an ac voltmeter with full-wave rectification. Compute the values of the peak-to-peak voltage and the

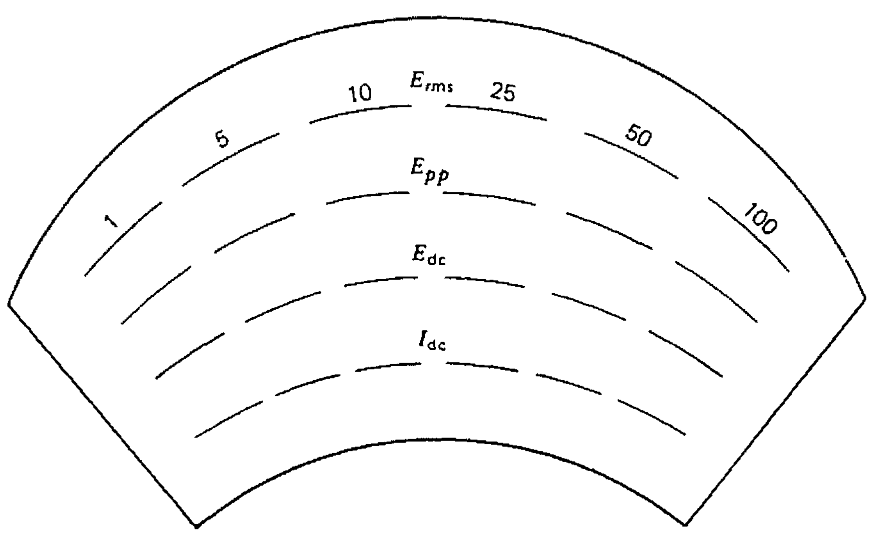

FIGURE 3-25 Meter scale for Problem 3-7.

dc voltage and current for the rms voltages shown if the dc sensitivity of the meter movement is 10 kΩ/V. Sketch the meter face and fill in the blanks.

3-8 Calculate the dc sensitivity and the value of the multiplier resistor required to limit current to the full-scale deflection current in the circuit shown in Fig. 3-26.

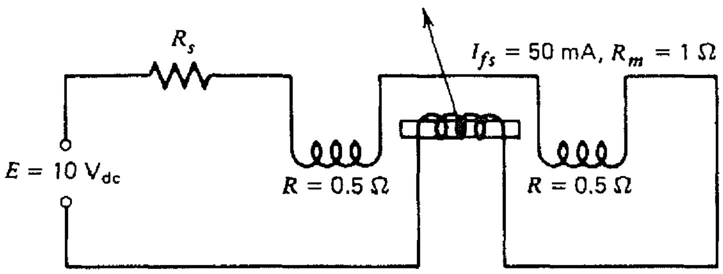

FIGURE 3-26 Circuit for Problem 3-8.

3-9 An rms ac voltmeter and a peak-to-peak-reading ac voltmeter are to be used to determine whether three ac signals are sinusoidal. Determine whether the signals are sinusoidal if the following readings are obtained

First signal	peak-to-peak reading	= 35.26 V
	rms reading	= 12.00 V
Second signal	peak-to-peak reading	= 11.31 V
	rms reading	= 4.00 V
Third signal	peak-to-peak reading	= 25.00 V
	rms reading	= 8.83 V

3-10 An ac voltmeter is to be used to measure the rms voltage across the 15-kΩ resistor in the circuit shown in Fig. 3-27. If the voltmeter uses half-wave rectification and a 100-μA d'Arsonval meter movement, if it is set on its 10-V range, and if R_m = 1.5 kΩ, what reading will be obtained?

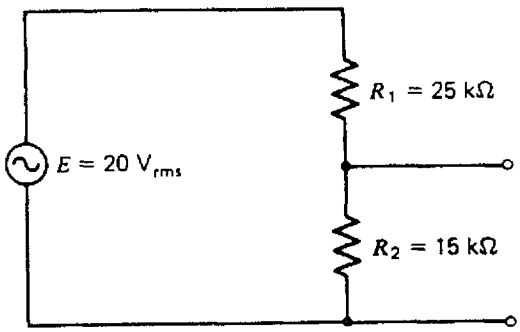

FIGURE 3-27 Circuit for Problem 3-10.

3-11 Two different ac voltmeters are used to measure the voltage across the 22-kΩ resistor in the circuit shown in Fig. 3-28. Meter A has ac

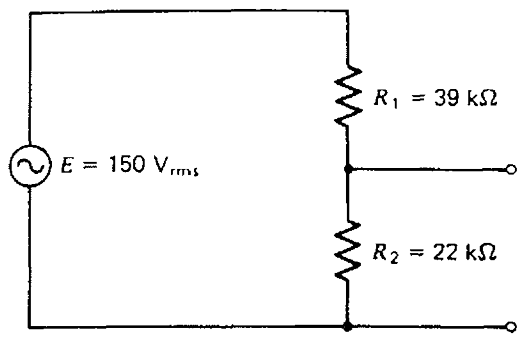

FIGURE 3-28 Circuit for Problem 3-11.

sensitivity of 10 kΩ/V, a guaranteed accuracy of 98% at full scale, and is set on its 200-V range. Meter B has an ac sensitivity of 4 kΩ/V, a guaranteed accuracy of 98.5% at full scale, and is set on its 100-V range. Which meter will provide a more accurate result?

3-12 The ac voltmeter described below is used to measure the voltage across the 68-kΩ resistor in the circuit shown in Fig. 3-29. What is the minimum voltage reading that should be observed? The ac voltmeter has

- Full-wave rectification.
- 100-μA meter movement.
- 150-V range.
- Limiting error of ±3% at full scale. (Refer to Chapter 1 for a discussion of limiting error.)

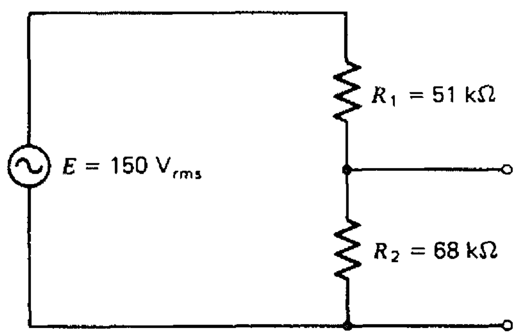

FIGURE 3-29 Circuit for Problem 3-12.

II LABORATORY EXPERIMENTS

Laboratory experiments E5 and E6 apply the theory that has been presented in Chapter 3. The purpose of these experiments is to provide hands-on experience to reinforce the theory.

The equipment required to perform the experiments can be found in any well-equipped electronics laboratory. The second experiment calls for three specific types of meter movements. If these are not available, any meter movements that respond to alternating current can be used.

The contents of the laboratory report to be submitted by each student are listed at the end of each experimental procedure.