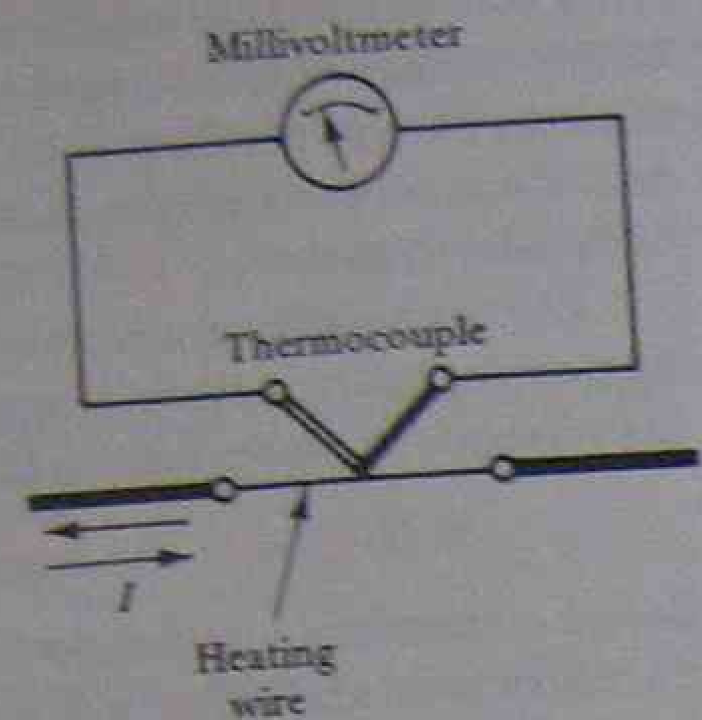
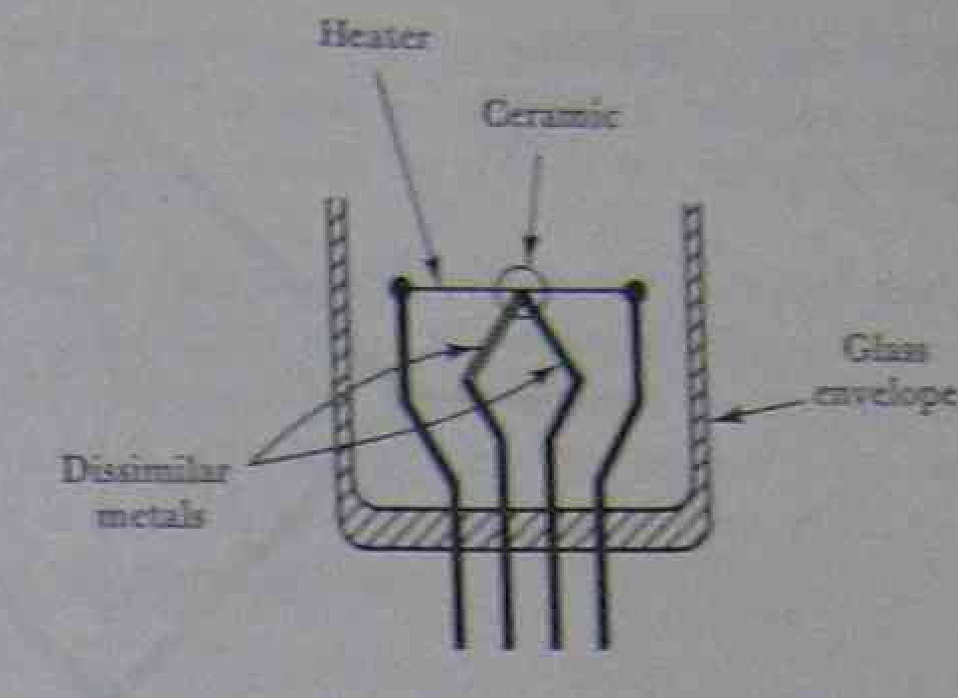


FIGURE 2-20. Basic thermocouple instrument.

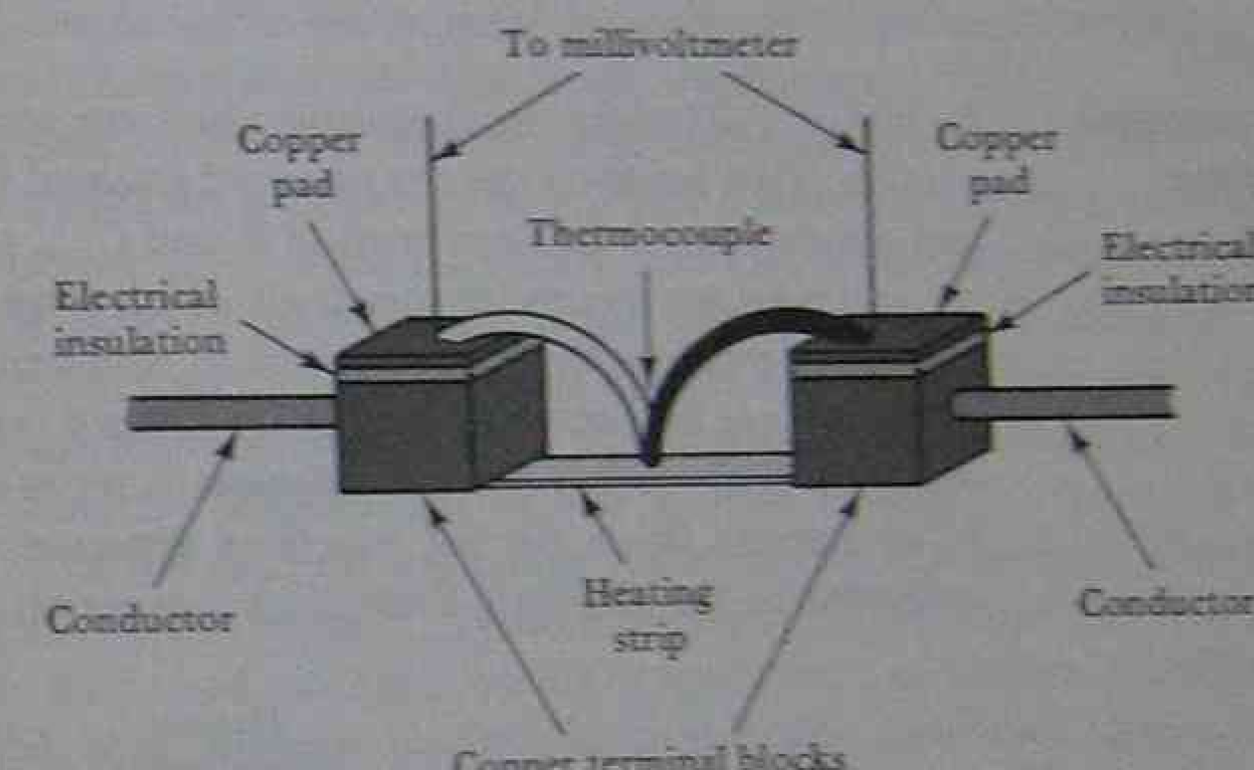
junction from loss of heat. The junction may be directly welded to the heater, or it may be thermally (but not electrically) connected to the heater by a bead of ceramic material.

In Figure 2-21(b) a thermocouple with a flat heating conductor is shown. The ends of the thermocouple wires are connected to copper pads which are electrically insulated from the heater. Although electrically insulated, the copper pads are in thermal contact with the large copper terminal blocks of the heater. This has the effect of keeping the ends of the thermocouple wires at the same ambient temperature as the terminal blocks. Thus, the thermocouple junction is heated, but the ends of the wires are at the normal (relatively cold) temperature of the terminals. When no current flows, both ends of each thermocouple wire are maintained at ambient temperature, and no voltage is generated. When the current flows, the junction of the dissimilar metal wires is heated, while the opposite ends remain at the ambient temperature. These opposite ends are electrically connected together through the millivoltmeter, so they can be termed a *cold junction*. This condition, of a hot junction and a cold junction in the thermocouple circuit, is the requirement for maximum emf generation. Since the thermocouple wires are maintained at the same ambient temperature when no current is flowing, the emf generated at the heated junction results only from the heating effect of the current. The device just described [Figure 2-21(b)] is termed a *compensated thermocouple*, meaning that it is compensated against the effects of any change in ambient temperature.

Some of the most common materials used as thermocouple pairs are Iron-Constantan, Copper-Constantan, Chromel-Alumel, and Platinum-platinum/Rhodium. Thermocouple junctions can survive very high temperatures and are used as temperature transducers. However, when used in a measuring instrument, the typical maximum heater temperature is about 300°C. The typical maximum thermocouple output at this temperature is around 12 mV. Heating element currents range from 2 mA to 50 mA.



(a) Thermocouple in a vacuum tube



(b) Compensated thermocouple

FIGURE 2-21. Two types of thermocouples.

2-7-2 Thermocouple Ammeters and Voltmeters

A thermocouple instrument can be used directly as an ammeter, and shunts can be employed to expand its range of current measurement. By connecting multiplier resistors in series with the heater, a voltmeter can be constructed. The sensitivity of thermocouple voltmeters is considerably lower than that of a PMMC voltmeter. However, thermocouple instruments indicate true rms value, no matter what the waveform of the applied voltage or current. They can also be used as transfer instruments; calibrated on dc and then employed to measure either ac or dc. Furthermore, thermocouple instruments can be used from dc to very high frequencies, 50 MHz and higher. The frequency limit, in fact, is due not to the thermocouple but to the capacitance and inductance of connecting leads and series resistors.

2

DEFLECTION TYPE AMMETERS, VOLTMETERS, AND WATTMETERS

INTRODUCTION

All deflection type instruments are essentially current meters. In the case of the ammeter, the current to be measured (or a portion of it) passes through the instrument and produces pointer deflection. A voltmeter is simply a very low current ammeter with a high resistance. The current that flows in a voltmeter is directly proportional to the applied voltage, and the instrument scale is calibrated to indicate voltage.

A PMMC instrument can be employed directly as a dc voltmeter or ammeter. When connected with rectifiers, it can be used as an ac voltmeter. Together with a current transformer and rectifiers, the PMMC instrument functions as an ac ammeter.

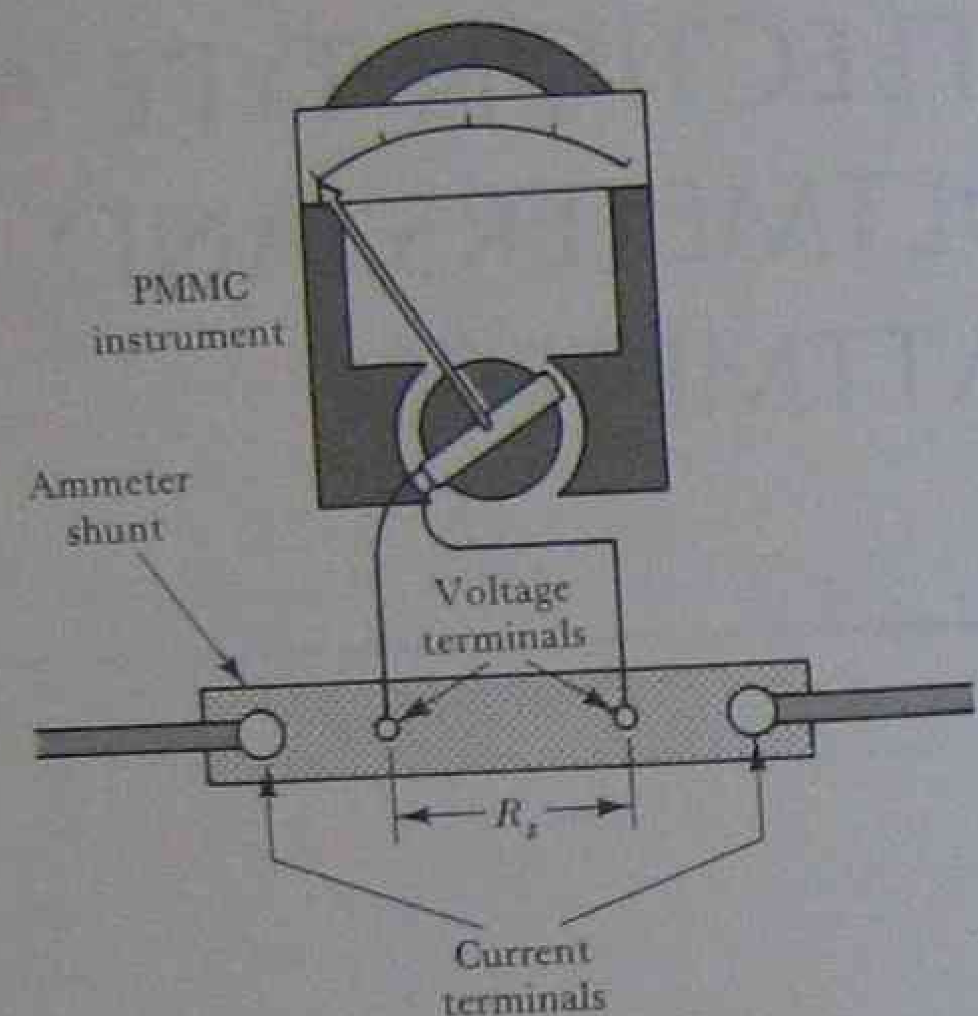
An electrodynamic instrument can be used on ac or dc, as an ammeter, a voltmeter, or a wattmeter. Its most important application is as a wattmeter. In this situation, the field coils pass the load current, and the moving coil carries a current proportional to the supply voltage.

In thermocouple instruments, thermocouples are used to generate a voltage proportional to the heating effect of a current. Thermocouple voltmeters, ammeters, and wattmeters can be constructed. They function on dc or ac and can operate satisfactorily to very high frequencies.

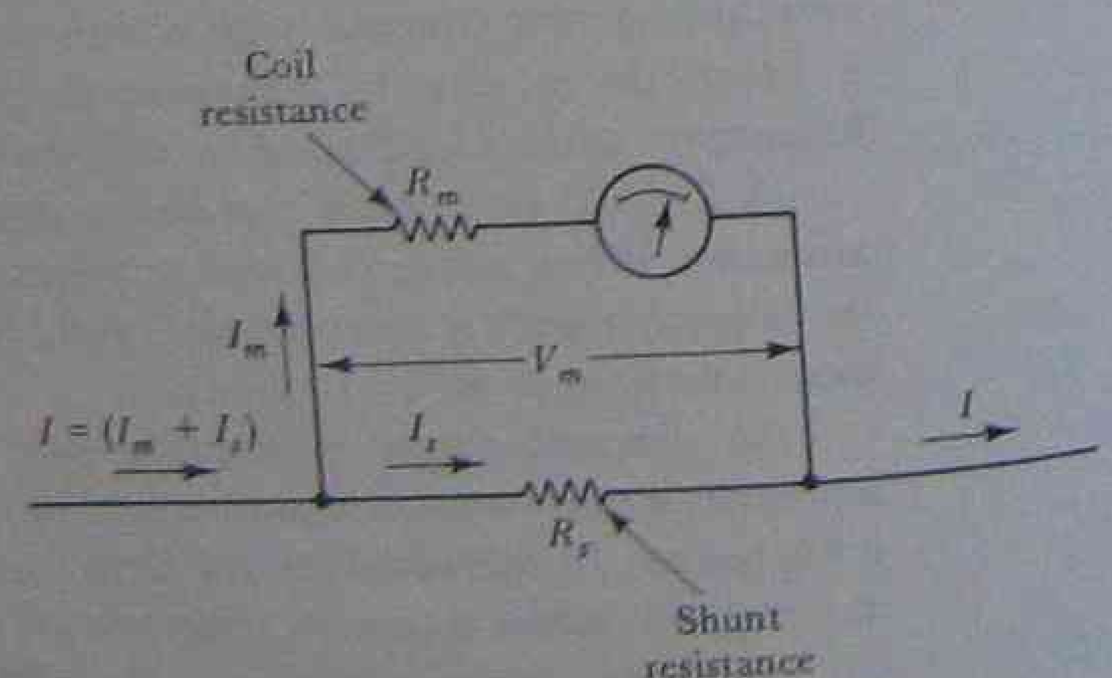
2-1 DC AMMETER

2-1-1 Operation

The PMMC instrument is an ammeter. Pointer deflection is directly proportional to the current flowing in the coil. However, maximum pointer deflection is produced by a very small current, and the coil is usually wound of thin wire that would be quickly destroyed by large currents. For larger currents, the instrument must be modified so that most of the



(a) Construction of dc ammeter



(b) Ammeter circuit

FIGURE 2-1. dc ammeter construction and circuit diagram.

current to be measured is shunted around the coil of the meter. Only a small portion of the current passes through the moving coil. Figure 2-1 illustrates how this is arranged.

A *shunt*, or very low resistance, is connected in parallel with the instrument coil [Figure 2-1(a)]. The shunt has two sets of terminals identified as *voltage terminals* and *current terminals*. This is to ensure that the resistance in parallel with the coil (R_s) is accurately defined and the contact resistance of the current terminals is removed from R_s. Contact resistance can vary with change in current level and thus introduce errors.

In the circuit diagram in Figure 2-1(b), r_m is the meter resistance (or coil circuit resistance) and R_s is the resistance of the shunt. Suppose the meter resistance is exactly 99 Ω and the shunt resistance is 1 Ω. The shunt current (I_s) will be ninety-nine times the meter current (I_m). In this situation, if the meter gives FSD for a coil current of 0.1 mA, the scale should be calibrated to read 100 × 0.1 mA or 10 mA at full scale. The relationship between shunt current and coil current is further investigated in Examples 2-1 and 2-2.

EXAMPLE 2-1

An ammeter (as in Figure 2-1) has a PMMC instrument with a coil resistance of $R_m = 99\ \Omega$ and FSD current of 0.1 mA. Shunt resistance $R_s = 1\ \Omega$. Determine the total current passing through the ammeter at (a) FSD, (b) 0.5 FSD, and (c) 0.25 FSD.

SOLUTION

a. At FSD:

$$\text{meter voltage } V_m = I_m R_m \qquad \text{[see Figure 2-1(b)]}$$
$$= 0.1\text{ mA} \times 99\ \Omega$$
$$= 9.9\text{ mV},$$

shunt voltage = meter voltage,

$$I_s R_s = V_m$$
$$I_s = \frac{V_m}{R_s} = \frac{9.9\text{ mV}}{1\ \Omega} = 9.9\text{ mA},$$

$$\text{total current } I = I_s + I_m$$
$$= 9.9\text{ mA} + 0.1\text{ mA} = 10\text{ mA}.$$

b. At 0.5 FSD:

$$I_m = 0.5 \times 0.1 \text{ mA} = 0.05 \text{ mA},$$
$$V_m = I_m R_m = 0.05 \text{ mA} \times 99\ \Omega = 4.95 \text{ mV},$$
$$I_s = \frac{V_m}{R_s} = \frac{4.95 \text{ mV}}{1\ \Omega} = 4.95 \text{ mA},$$
$$\text{total current } I = I_s + I_m$$
$$= 4.95 \text{ mA} + 0.05 \text{ mA} = 5 \text{ mA}.$$

c. At 0.25 FSD:

$$I_m = 0.25 \times 0.1 \text{ mA} = 0.025 \text{ mA},$$
$$V_m = I_m R_m = 0.025 \text{ mA} \times 99\ \Omega$$
$$= 2.475 \text{ mV},$$
$$I_s = \frac{V_m}{R_s} = \frac{2.475 \text{ mV}}{1\ \Omega} = 2.475 \text{ mA},$$
$$\text{total current } I = I_s + I_m$$
$$= 2.475 \text{ mA} + 0.025 \text{ mA} = 2.5 \text{ mA}.$$

2-1-2 Scale

In Example 2-1 the total ammeter current is 10 mA when the moving-coil instrument indicates FSD. Therefore, the meter scale can be calibrated so

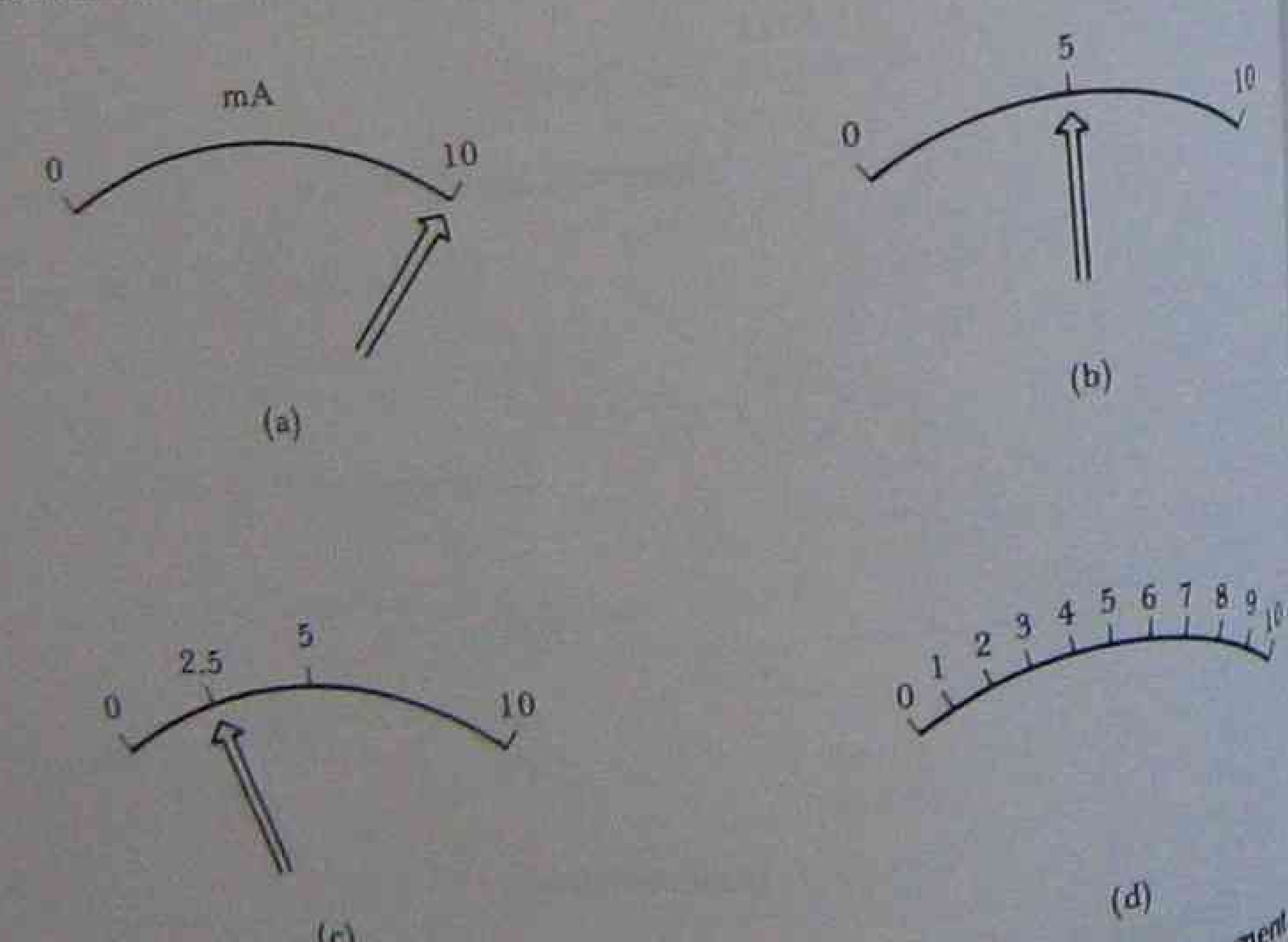


FIGURE 2-2. Linear scale of a dc ammeter using a PMMC instrument.

that FSD represents 10 mA [see Figure 2-2(a)]. When the pointer indicates 0.5 FSD and 0.25 FSD, the total current levels are 5 mA and 2.5 mA, respectively [Figures 2-2(b) and (c)].

It is seen that the ammeter scale can be calibrated linearly to represent all current levels from 0 to 10 mA [Figure 2-2(d)].

2-1-3 Shunt Resistance

Refer again to Example 2-1. If a shunt having a smaller resistance is used, the shunt current and the total meter current will be larger than the levels calculated. In fact, shunt resistance values can be determined to convert a PMMC instrument into an ammeter for measuring virtually any desired level of current. Example 2-2 demonstrates how shunt resistances are calculated.

EXAMPLE 2-2

A PMMC instrument has a FSD of 100 μA and a coil resistance of 1 kΩ. Calculate the required shunt resistance value to convert the instrument into an ammeter: (a) with FSD = 100 mA and (b) with FSD = 1 A.

SOLUTION

a. FSD = 100 mA:

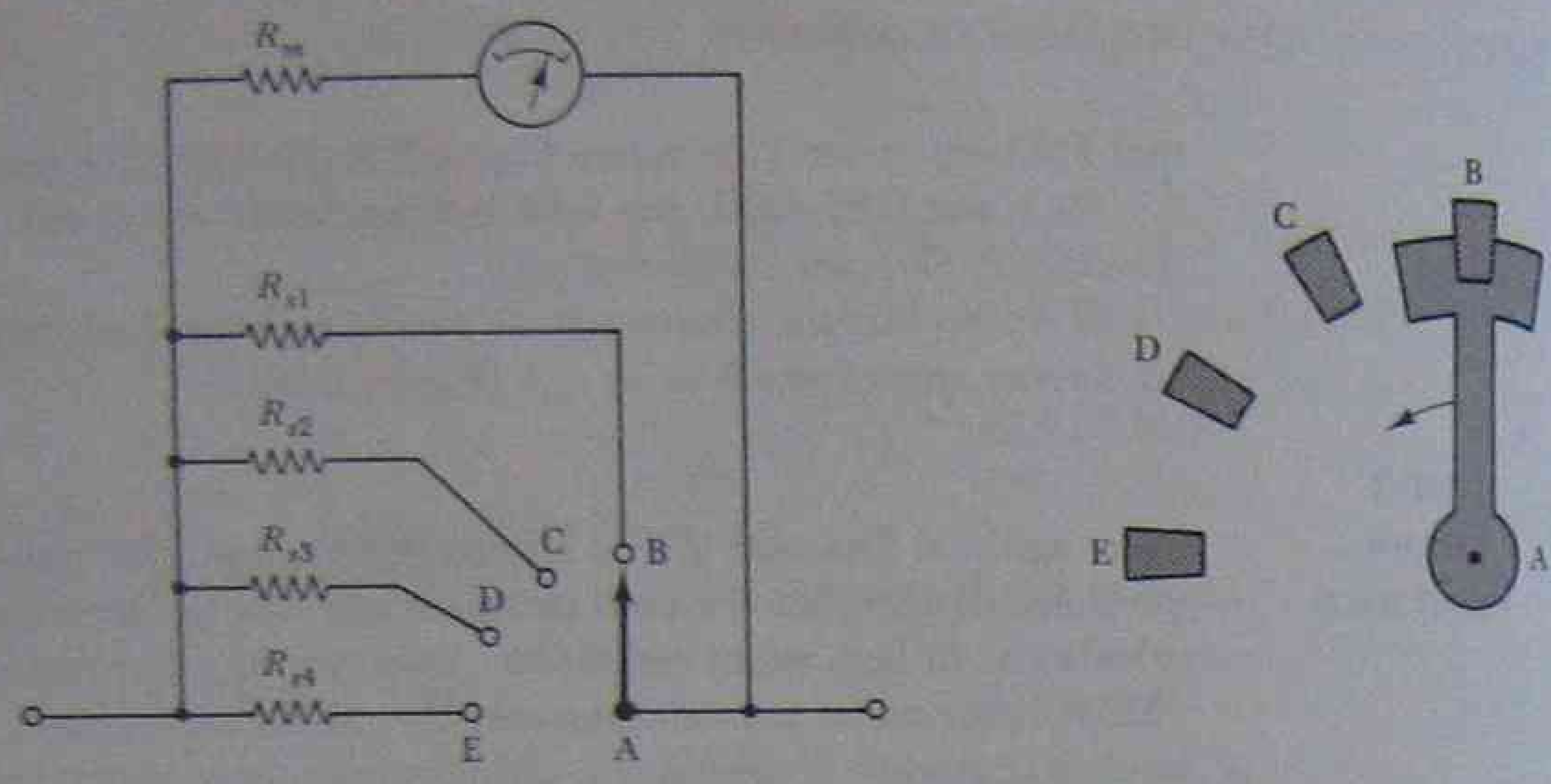
$$V_m = I_m R_m = 100\ \mu A \times 1 \text{ k}\Omega = 100 \text{ mV},$$
$$I = I_s + I_m,$$
$$I_s = I - I_m = 100 \text{ mA} - 100\ \mu\text{A} = 99.9 \text{ mA},$$
$$R_s = \frac{V_m}{I_s} = \frac{100 \text{ mV}}{99.9 \text{ mA}} = 1.001\ \Omega.$$

b. FSD = 1 A:

$$V_m = I_m R_m = 100 \text{ mV},$$
$$I_s = I - I_m = 1 \text{ A} - 100\ \mu\text{A} = 999.9 \text{ mA},$$
$$R_s = \frac{V_m}{I_s} = \frac{100 \text{ mV}}{999.9 \text{ mA}} = 0.10001\ \Omega.$$

2-1-4 Multirange Ammeters

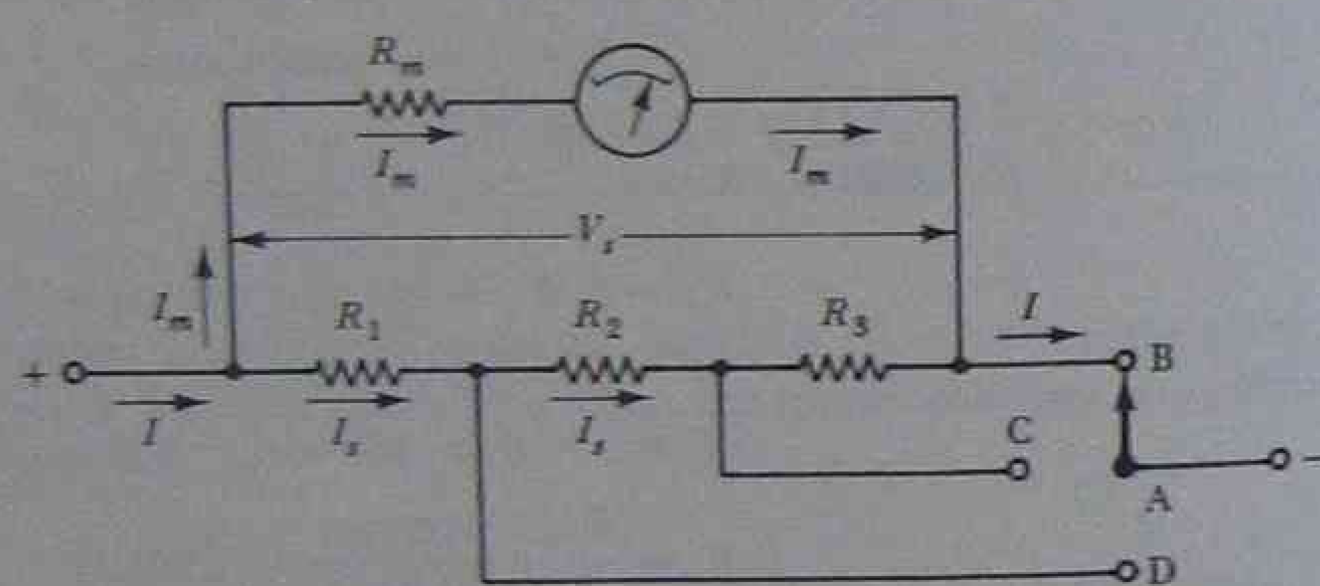
The circuit of a multirange ammeter is shown in Figure 2-3(a). As illustrated, a rotary switch is employed to select any one of several shunts having different resistance values. A *make-before-break switch* [Figure 2-3(b)] must be used so that the instrument is not left without a shunt in parallel with it even for a brief instant. If this occurred, the high resistance of the instrument would affect the current flowing in the circuit. More im-



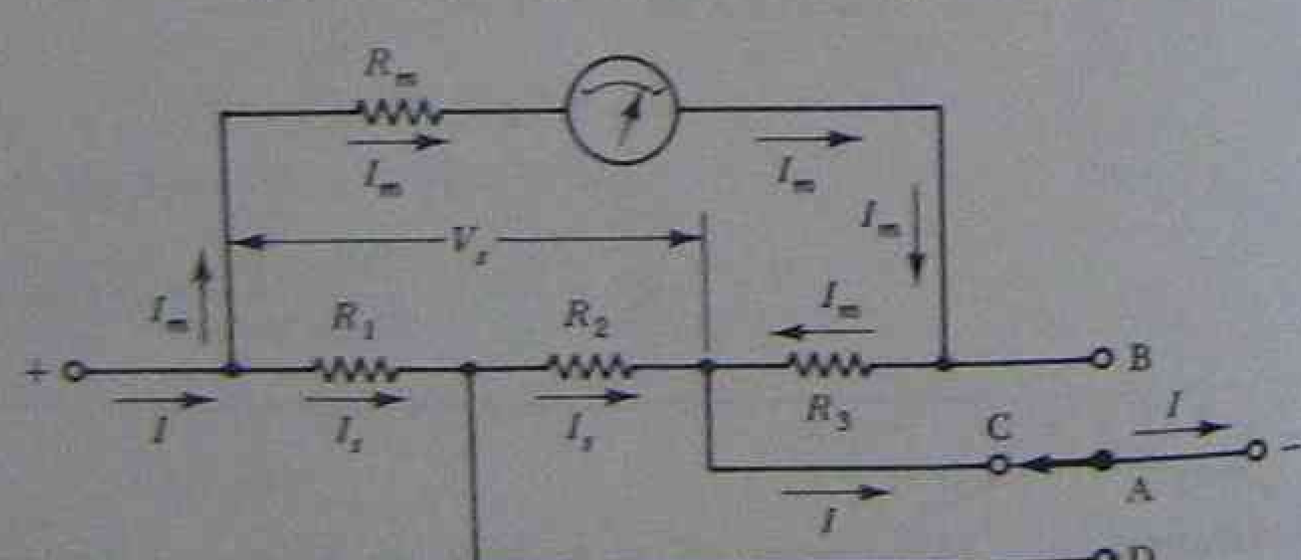
(a) Multirange ammeter using switched shunts

(b) Make-before-break switch

FIGURE 2-3. Multirange ammeter and range-changing switch.



(a) $(R_1 + R_2 + R_3)$ in parallel with R_m



(b) $(R_1 + R_2)$ in parallel with $(R_m + R_3)$

FIGURE 2-4. Multirange ammeter using an Ayrton shunt.

portantly, a current large enough to destroy the instrument might flow through its moving coil. When switching between shunts, the wide-ended moving contact of the make-before-break switch makes contact with the next terminal before it breaks contact with the previous terminal. Thus, during switching there are actually two shunts in parallel with the instrument.

Figure 2-4 shows another method of protecting the deflection instrument of an ammeter from excessive current flow when switching between shunts. Resistors R_1, R_2, and R_3 constitute an *Ayrton shunt*. In Figure 2-4(a) the switch is at contact B, and the total resistance in parallel with the instrument is $R_1 + R_2 + R_3$. The meter resistance remains R_m. When the switch is at contact C [Figure 2-4(b)], the resistance R_3 is in series with the meter, and $R_1 + R_2$ is in parallel with $R_m + R_3$. Similarly, with the switch at contact D, R_1 is in parallel with $R_m + R_2 + R_3$. Because the shunts are permanently connected, and the switch makes contact with the shunt junctions, the deflection instrument is never left without a parallel-connected shunt (or shunts). In Example 2-3 ammeter current ranges are calculated for each switch position on an Ayrton shunt.

EXAMPLE 2-3

A PMMC instrument has a three-resistor Ayrton shunt connected across it to make an ammeter, as in Figure 2-4. The resistance values are $R_1 = 0.05\ \Omega$, $R_2 = 0.45\ \Omega$, and $R_3 = 4.5\ \Omega$. The meter has $R_m = 1\ \text{k}\Omega$ and FSD = 50 μA. Calculate the three ranges of the ammeter.

SOLUTION

Refer to Figure 2-4

Switch at contact B:

$$V_s = I_m R_m = 50\ \mu\text{A} \times 1\ \text{k}\Omega = 50\ \text{mV},$$

$$I_s = \frac{V_s}{R_1 + R_2 + R_3}$$

$$= \frac{50\ \text{mV}}{0.05\ \Omega + 0.45\ \Omega + 4.5\ \Omega} = 10\ \text{mA},$$

$$I = I_m + I_s = 50\ \mu\text{A} + 10\ \text{mA}$$

$$= 10.05\ \text{mA}.$$

Ammeter range = 10 mA.

Switch at contact C:

$$
\begin{aligned}
V_s &= I_m(R_m + R_3) \\
&= 50\ \mu\text{A}(1\ \text{k}\Omega + 4.5\ \Omega) \\
&= 50\ \text{mV}, \\
I_s &= \frac{V_s}{(R_1 + R_2)} \\
&= \frac{50\ \text{mV}}{(0.05\ \Omega + 0.45\ \Omega)} \\
&= 100\ \text{mA}, \\
I &= 50\ \mu\text{A} + 100\ \text{mA} \\
&= 100.05\ \text{mA}.
\end{aligned}
$$

Ammeter range = 100 mA.

Switch at contact D:

$$
\begin{aligned}
V_s &= I_m(R_m + R_3 + R_2) \\
&= 50\ \mu\text{A}(1\ \text{k}\Omega + 4.5\ \Omega + 0.45\ \Omega) \\
&= 50\ \text{mV}, \\
I_s &= \frac{V_s}{R_1} = \frac{50\ \text{mV}}{0.05\ \Omega} \\
&= 1\ \text{A}, \\
I &= 50\ \mu\text{A} + 1\ \text{A} \\
&= 1.00005\ \text{A}.
\end{aligned}
$$

Ammeter range = 1 A.

2-1-5 Temperature Error

The moving coil in a PMMC instrument is wound with thin copper wire, and its resistance can change significantly when its temperature changes. The heating effect of the coil current may be enough to produce a resistance change. Any such change in coil resistance will introduce an error in ammeter current measurements. To minimize the effect of coil resistance variation, a *swamping resistance* made of *manganin* or *constantan* is connected in series with the coil, as illustrated in Figure 2-5. Manganin and constantan have resistance temperature coefficients very close to zero. If

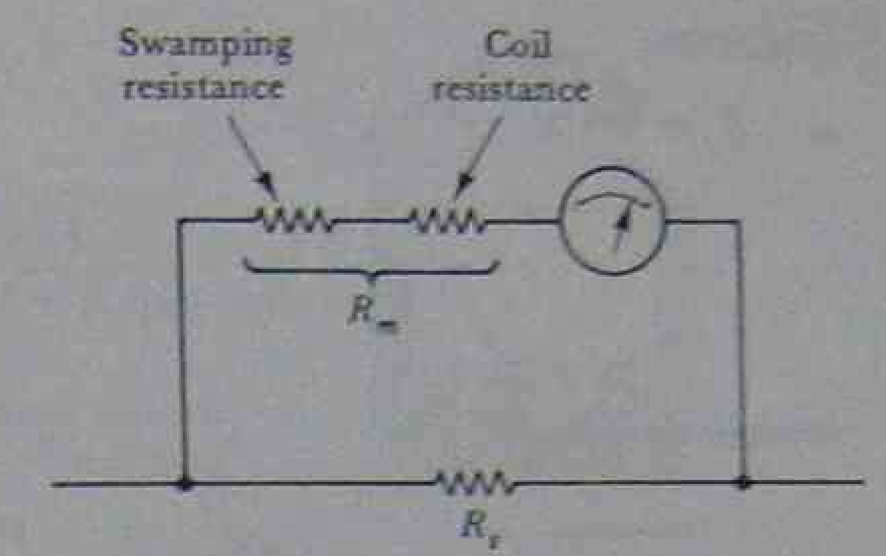


FIGURE 2-5. Use of a swamping resistance to minimize temperature errors in an ammeter.

the swamping resistance is nine times the coil resistance, then a 1% change in coil resistance would result in a total (swamping plus coil) resistance change of 0.1%.

The ammeter shunt must also be made of manganin or constantan to avoid shunt resistance variations with temperature. As noted in Figure 2-5, the swamping resistance must be considered part of the meter resistance r_m when calculating shunt resistance values.

2-1-6 Ammeter Resistance

An ammeter is always connected in series with a circuit in which current is to be measured. To avoid affecting the current level in the circuit, the ammeter must have a resistance much lower than the circuit resistance. Therefore, ammeter resistance is an important quantity. In Examples 2-2 and 2-3 the ammeter resistances are essentially the same as the total shunt resistance in parallel with the deflection instrument.

EXAMPLE 2-4

An ammeter is connected to measure the current in a 10-Ω load supplied from a 10-V source (see Figure 2-6). Calculate the circuit current if the ammeter resistance (R_a) is (a) 0.1 Ω or (b) 1 Ω. Also, in each case, calculate the effect of the ammeter on the current level.

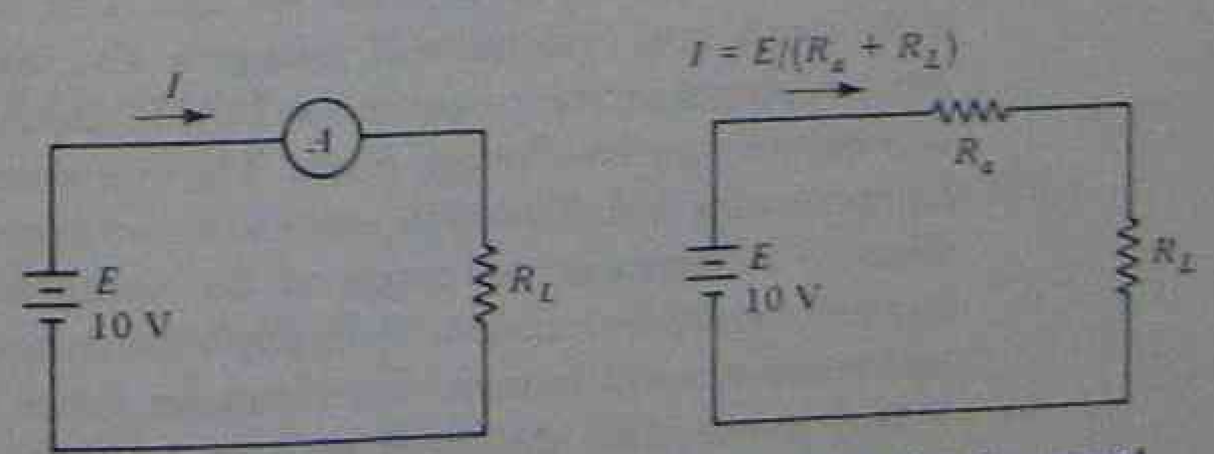


FIGURE 2-6. Ammeter resistance can affect circuit current.

SOLUTION

a. $R_a = 0.1\ \Omega$

$$I = \frac{E}{R_L + R_a} = \frac{10\text{ V}}{10\ \Omega + 0.1\ \Omega} = 0.99\text{ A}$$

Without the ammeter,

$$I = \frac{E}{R_L} = \frac{10\text{ V}}{10}$$

$$= 1\text{ A},$$

$$\textit{effect of ammeter} = \frac{(1\text{ A} - 0.99\text{ A})}{1\text{ A}}(100\%) = 1\%.$$

b. $R_a = 1\ \Omega$

$$I = \frac{E}{R_L + R_a} = \frac{10\text{ V}}{10\ \Omega + 1\ \Omega} = 0.909\text{ A},$$

$$\textit{effect of ammeter} = \frac{1\text{ A} - 0.909\text{ A}}{1\text{ A}}(100\%) = 9.1\%.$$

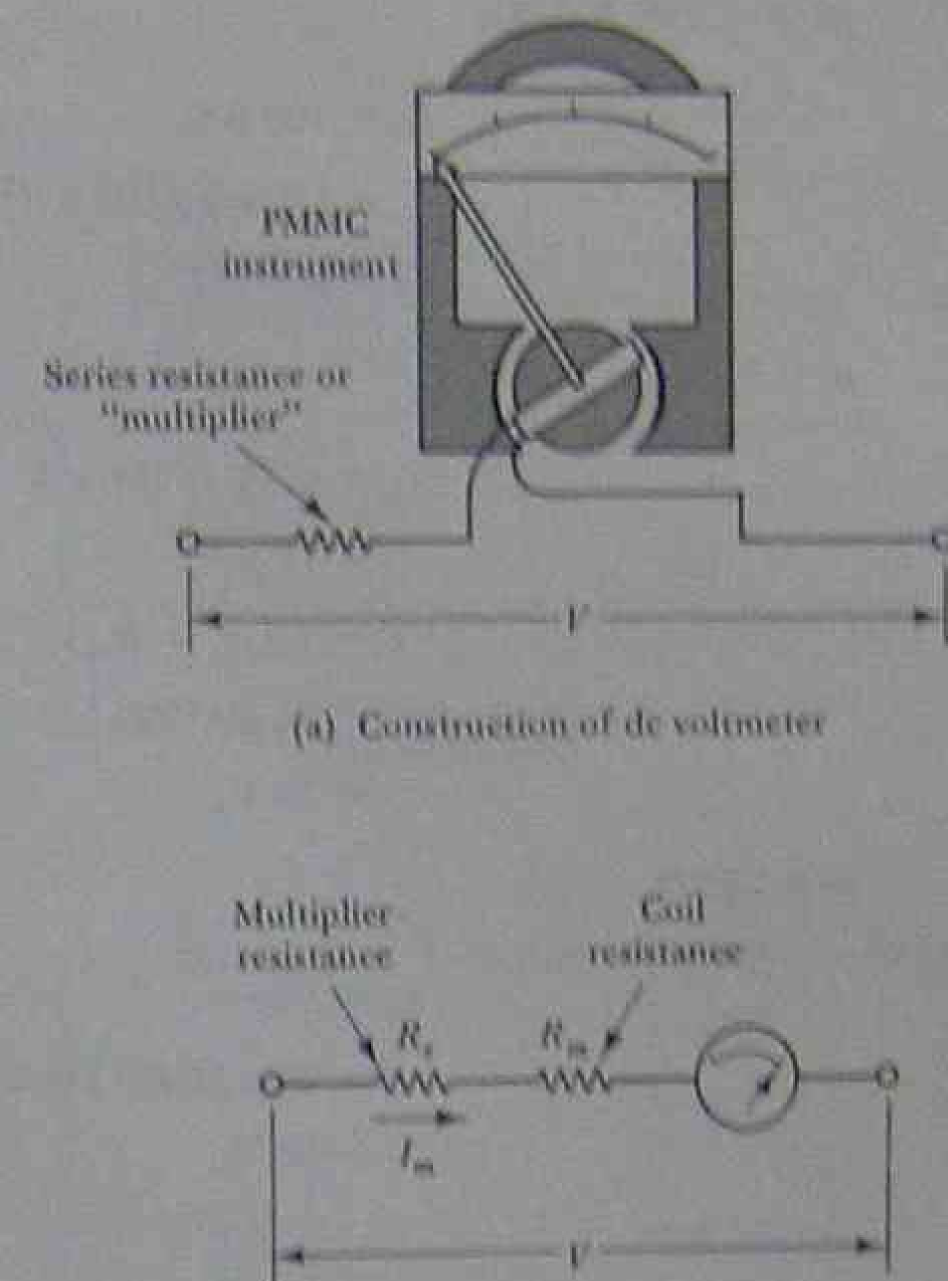
2-1-7 Using Ammeters

The procedure for using a multirange ammeter is exactly as listed in Section 3-5 for a multifunction instrument.

2-2 DC VOLTMETER

2-2-1 Operation

The deflection of a PMMC instrument is proportional to the current flowing through the moving coil. The coil current is directly proportional to the voltage across the coil. Therefore, the scale of the PMMC meter could be calibrated to indicate voltage. The coil resistance is normally quite small, and thus the coil voltage is also usually very small. Without any additional series resistance the PMMC instrument would only be able to measure very low voltage levels. The voltmeter range is easily increased by connecting a resistance in series with the instrument [see Figure 2-7(a)]. Because it increases the range of the voltmeter, the series resistance is termed a *multiplier resistance.* A multiplier resistance which is nine times the coil resistance will increase the voltmeter range by a factor of 10. Figure 2-7(b) shows that the total resistance of the voltmeter is (multiplier resistance) + (coil resistance).



(a) Construction of dc voltmeter

(b) Voltmeter circuit

FIGURE 2-7. dc voltmeter construction and circuit diagram.

EXAMPLE 2-5 A PMMC instrument with a FSD of 100 μA and a coil resistance of 1 kΩ is to be converted into a voltmeter. Determine the required multiplier resistance if the voltmeter is to measure 100 V at full scale. Also calculate the applied voltage when the instrument indicates 0.75, 0.5, and 0.25 of FSD.

SOLUTION

$$V = I_m(R_s + R_m) \qquad \text{[see Figure 2-7(b)]},$$

$$R_s + R_m = \frac{V}{I_m},$$

and

$$R_s = \frac{V}{I_m} - R_m$$

for $V = 100$ *V FSD*,

$$I_m = 100\ \mu\text{A},$$
$$R_s = (100\ \text{V}/100\ \mu A) - 1\ \text{k}\Omega$$
$$= 999\ \text{k}\Omega.$$

At 0.75 FSD:

$$I_m = 0.75 \times 100\ \mu\text{A}$$
$$= 75\ \mu\text{A},$$
$$V = I_m(R_s + R_m)$$
$$= 75\ \mu\text{A}(999\ \text{k}\Omega + 1\ \text{k}\Omega)$$
$$= 75\ \text{V}.$$

at 0.5 FSD:

$$I_m = 50\ \mu\text{A},$$
$$V = 50\ \mu\text{A}(999\ \text{k}\Omega + 1\ \text{k}\Omega)$$
$$= 50\ \text{V}.$$

at 0.25 FSD:

$$I_m = 25\ \mu\text{A},$$
$$V = 25\ \mu\text{A}(999\ \text{k}\Omega + 1\ \text{k}\Omega)$$
$$= 25\ \text{V}.$$

Example 2-5 demonstrates that the PMMC voltmeter has the linear scale shown in Figure 2-8.

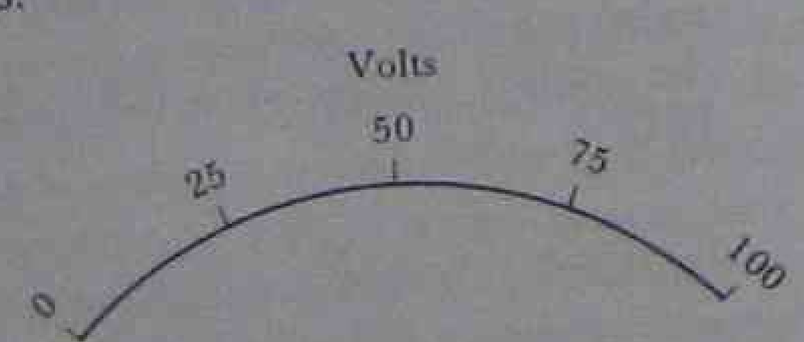
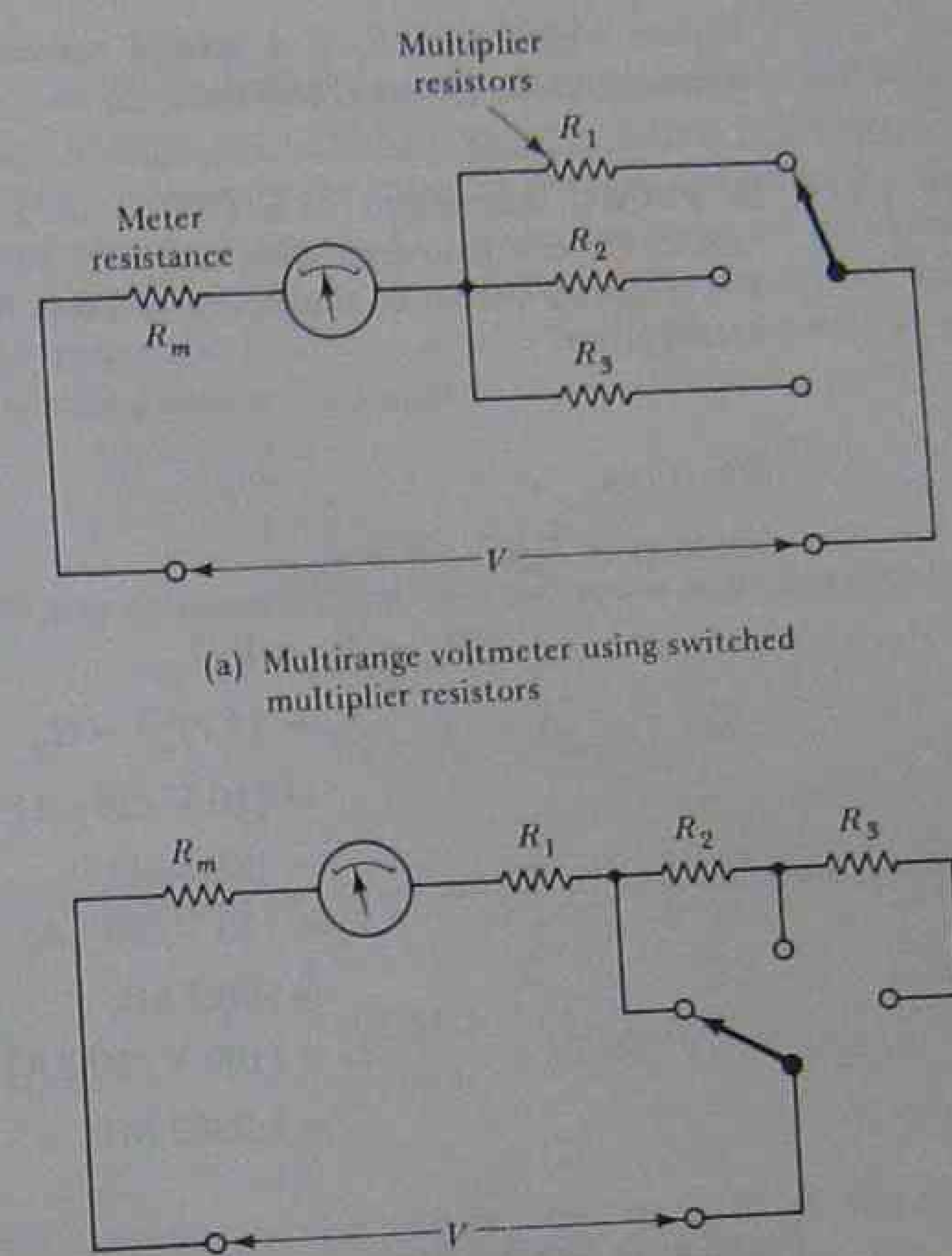


FIGURE 2-8. Voltmeter scale for Example 2-5.

2-2-2 Multirange Voltmeters

A multirange voltmeter consists of a deflection instrument, several multiplier resistors, and a rotary switch. Two possible circuits are illustrated in Figure 2-9. In Figure 2-9(a) only one of the three multiplier resistors is



(a) Multirange voltmeter using switched multiplier resistors

(b) Multirange voltmeter using series-connected multiplier resistors

FIGURE 2-9. Multirange voltmeter circuits.

connected in series with the meter at any time. The range of this voltmeter is

$$V = I_m(R_m + R)$$

where R can be R_1, R_2, or R_3.

In Figure 2-9(b) the multiplier resistors are connected in series, and each junction is connected to one of the switch terminals. The range of this voltmeter can also be calculated from the equation $V = I_m(R_m + R)$, where R can now be R_1, $R_1 + R_2$, or $R_1 + R_2 + R_3$.

Of the two circuits, the one in Figure 2-9(b) is the least expensive to construct. This is because (as shown in Example 2-6) all of the multiplier resistors in Figure 2-9(a) must be special (nonstandard) values, while in

Figure 2-9(b) only R_1 is a special resistor and all other multipliers are standard value (precise) resistors.

EXAMPLE 2-6

A PMMC instrument with FSD = 50 μA and $R_m = 1700\ \Omega$ is to be employed as a voltmeter with ranges of 10 V, 50 V, and 100 V. Calculate the required values of multiplier resistors for the circuits of Figure 2-9(a) and (b).

SOLUTION

Circuit as in Figure 2-9(a):

$$
\begin{aligned}
R_m + R_1 &= V/I_m, \\
R_1 &= (V/I_m) - R_m \\
&= (10\ \text{V}/50\ \mu\text{A}) - 1700\ \Omega \\
&= 198.3\ \text{k}\Omega, \\
R_2 &= (50\ \text{V}/50\ \mu\text{A}) - 1700\ \Omega \\
&= 998.3\ \text{k}\Omega, \\
R_3 &= (100\ \text{V}/50\ \mu\text{A}) - 1700\ \Omega \\
&= 1.9983\ \text{M}\Omega.
\end{aligned}
$$

Circuit as in Figure 2-9(b):

$$
\begin{aligned}
R_m + R_1 &= V_1/I_m, \\
R_1 &= (V_1/I_m) - R_m \\
&= (10\ \text{V}/50\ \mu\text{A}) - 1700\ \Omega \\
&= 198.3\ \text{k}\Omega, \\
R_m + R_1 + R_2 &= V_2/I_m, \\
R_2 &= (V_2/I_m) - R_1 - R_m \\
&= \frac{50\ \text{V}}{50\ \mu\text{A}} - 198.3\ \text{k}\Omega - 1700\ \Omega \\
&= 800\ \text{k}\Omega, \\
R_m + R_1 + R_2 + R_3 &= V_3/I_m \\
R_3 &= (V_3/I_m) - R_2 - R_1 - R_m \\
&= \frac{100\ \text{V}}{50\ \mu\text{A}} - 800\ \text{k}\Omega - 198.3\ \text{k}\Omega - 1700\ \Omega \\
&= 1\ \text{M}\Omega.
\end{aligned}
$$

2-2-3 Temperature Error

As in the case of the PMMC ammeter, the change in coil resistance with temperature change can introduce an error into a voltmeter. The solution to the problem is exactly the same as that for the ammeter. A swamping resistance made of manganin or constantan must be connected in series with the coil. However, in the voltmeter the multiplier performs the swamping resistance function, so the multiplier resistor is simply constructed of manganin or constantan.

2-2-4 Voltmeter Sensitivity

The voltmeter designed in Example 2-5 has a total resistance of:

$$R_V = R_s + R_m = 1\ \text{M}\Omega.$$

Since the instrument measures 100 V at full scale, its *resistance per volt* is:

$$\frac{1\ \text{M}\Omega}{100\ \text{V}} = 10\ \text{k}\Omega/\text{V}.$$

This quantity is also termed the *sensitivity* of the voltmeter. The sensitivity of a voltmeter is always specified by the manufacturer, and it is frequently printed on the scale of the instrument. If the sensitivity is known, the total voltmeter resistance is easily calculated. If the full-scale meter current is known, the sensitivity can be determined as the reciprocal of full-scale current. In Example 2-6, the PMMC meter gives FSD for 50 μA:

$$\text{sensitivity} = \frac{1}{50\ \mu\text{A}} = 20\ \text{k}\Omega/\text{V}.$$

Ideally, a voltmeter should have an extremely high resistance. A voltmeter is always connected across, or in parallel with, the points in a circuit at which the voltage is to be measured. If its resistance is too low, it can alter the circuit voltage. This is known as *voltmeter loading effect.*

EXAMPLE 2-7

A voltmeter on a 5-V range is connected to measure the voltage across R_2 in the circuit shown in Figure 2-10. Calculate V_{R2} (a) without the voltmeter connected, (b) with a voltmeter having a sensitivity of 20 kΩ/V, and (c) with a voltmeter having a sensitivity of 200 kΩ/V.

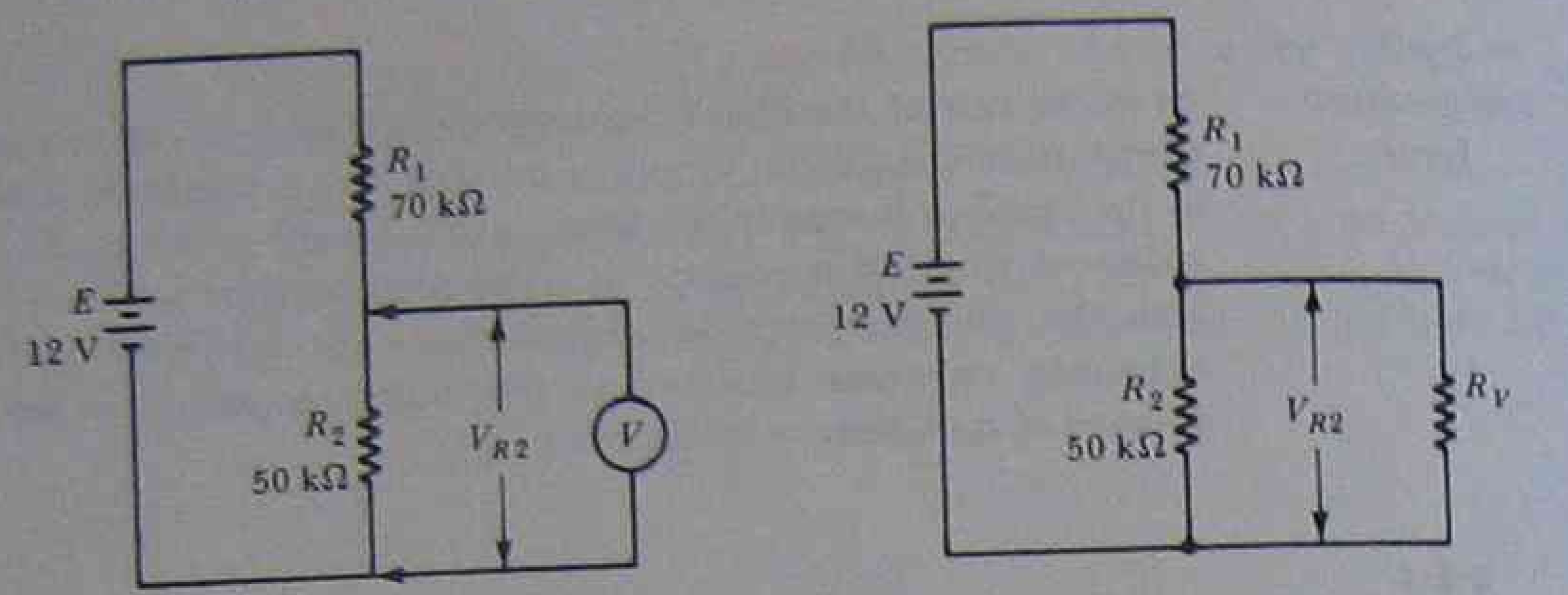


FIGURE 2-10. Voltmeter loading effect can alter the voltage within a circuit.

SOLUTION

a. *Without the voltmeter:*

$$V_{R2} = E\frac{R_2}{R_1 + R_2}$$

$$= 12\text{ V} \times \frac{50\text{ k}\Omega}{70\text{ k}\Omega + 50\text{ k}\Omega}$$

$$= 5\text{ V}.$$

b. *With 20 kΩ/V voltmeter:*

$$\textit{voltmeter resistance } R_v = 5\text{ V} \times 20\text{ k}\Omega/\text{V}$$

$$= 100\text{ k}\Omega,$$

$$R_v \| R_2 = 100\text{ k}\Omega \| 50\text{ k}\Omega$$

$$= 33.3\text{ k}\Omega,$$

$$V_{R2} = E\frac{R_v \| R_2}{R_1 + R_v \| R_2}$$

$$= 12\text{ V} \times \frac{33.3\text{ k}\Omega}{70\text{ k}\Omega + 33.3\text{ k}\Omega}$$

$$= 3.87\text{ V}.$$

c. *With a 200 kΩ/V voltmeter:*

$$R_v = 5\text{ V} \times 200\text{ k}\Omega/\text{V}$$

$$= 1\text{ M}\Omega,$$

$$R_v \| R_2 = 1\text{ M}\Omega \| 50\text{ k}\Omega$$

$$= 47.62\text{ k}\Omega,$$

$$V_{R2} = 12\text{ V} \times \frac{47.62\text{ k}\Omega}{70\text{ k}\Omega + 47.62\text{ k}\Omega}$$

$$= 4.86\text{ V}.$$

2-2-5 Using Voltmeters

The procedure for using a multirange voltmeter is exactly as listed in Section 3-6 for a multifunction instrument.

2-3 RECTIFIER VOLTMETERS

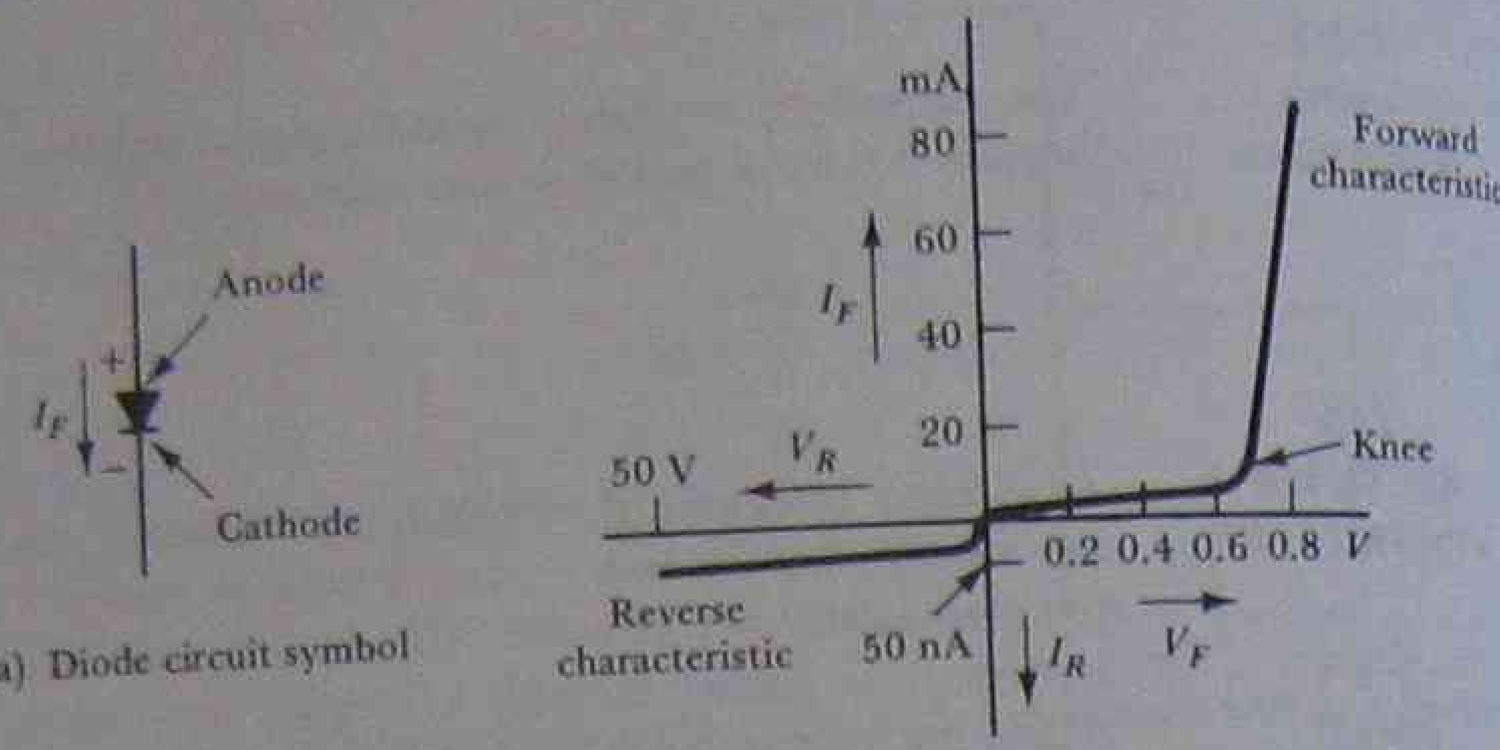
2-3-1 PMMC Instrument on ac

As already discussed, the PMMC instrument is *polarized*, i.e., its terminals are identified as + and −, and it must be correctly connected for positive (on-scale) deflection to occur. When an alternating current with a very low frequency is passed through a PMMC instrument, the pointer tends to follow the instantaneous level of the ac. As the current grows positively, the pointer deflection increases to a maximum at the peak of the ac. Then as the instantaneous current level falls, the pointer deflection decreases towards zero. When the ac goes negative, the pointer is deflected (off-scale) to the left of zero. This kind of pointer movement can occur only with ac having a frequency of perhaps 0.1 Hz or lower. With the normal 60-Hz supply frequencies, or higher frequencies, the damping mechanism of the instrument and the inertia of the meter movement prevents the pointer from following the changing instantaneous levels. Instead, the instrument pointer settles at the average value of the current flowing through the moving coil. The average value of purely sinusoidal ac is zero. Therefore, a PMMC instrument directly connected to measure 60-Hz ac indicates zero.

It is important to note that, although a PMMC instrument connected to an ac supply may be indicating zero, there can actually be a very large rms current flowing in its coils. In fact, sufficient current to destroy the instrument might easily flow while its pointer indicates zero.

2-3-2 Rectification

Rectifier instruments use silicon or germanium diodes to convert alternating current to a series of unidirectional current pulses, which produce positive deflection when passed through a PMMC instrument. Figure 2-11(a) shows the diode circuit symbol as an arrowhead and a bar. The arrowhead points in the direction of (conventional) current flow when the device is forward biased, i.e., from + to −. When correctly forward biased, a silicon diode typically has a forward volt drop (V_F) of 0.7 V, while a germanium diode has approximately 0.3 V. As illustrated in Figure 2-11(b), V_F increases slightly with increase in I_F, and if I_F falls to a very low level (below the knee of the characteristic) there can be a substantial drop in V_F. Usually, the device is assumed to have a constant forward volt drop when conducting. When reverse biased, the *reverse leakage current* that flows through the device is usually extremely small compared to the diode forward current.

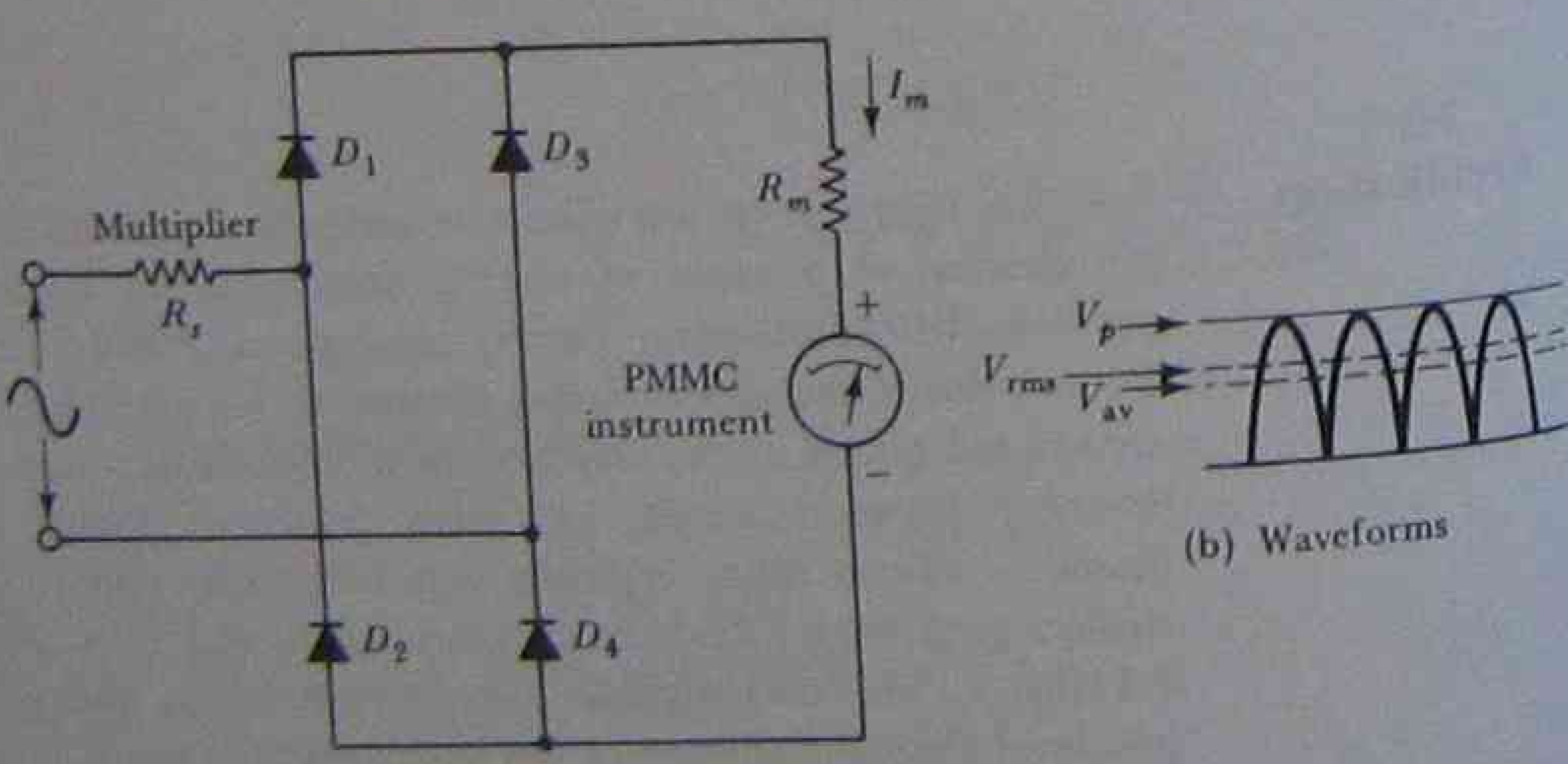


(a) Diode circuit symbol

(b) Characteristics of typical low current silicon diode

FIGURE 2-11. Diode circuit symbol and characteristics.

The full-wave bridge rectifier circuit in Figure 2-12(a) passes the positive half cycles of the sinusoidal input waveform and inverts the negative half cycles. When the input is positive, diodes D_1 and D_4 conduct, causing current to flow through the meter from top to bottom, as shown. When the input goes negative, D_2 and D_3 conduct, and current again flows through the meter from the positive terminal to the negative terminal. The resulting output is a series of positive half-cycles without any intervening spaces [see Figure 2-12(b)].



(a) Circuit

(b) Waveforms

FIGURE 2-12. ac voltmeter using a bridge rectifier and a PMMC instrument.

2-3-3 Full-wave Rectifier Voltmeter

As in the case of a dc voltmeter, the rectifier voltmeter circuit in Figure 2-12(a) uses a series-connected multiplier resistor to limit the current flow through the PMMC instrument. The actual current that flows in the instrument has the waveform illustrated in Figure 2-12(b). The meter deflection is proportional to the average current, which is 0.637 × peak current. But the actual current (or voltage) to be indicated in ac measurements is normally the rms quantity, which is 0.707 of the peak value, or 1.11 times the average value. Since there are direct relationships between rms, peak, and average values, the meter scale can be calibrated to indicate rms volts.

It must be noted that the above relationships between average, peak, and rms values apply only to pure sinusoidal waveforms. For nonsinusoidal waves, there are different factors relating the quantities.

EXAMPLE 2-8

A PMMC instrument with FSD = 100 μA and R_m = 1 kΩ is to be employed as an ac voltmeter with FSD = 100 V (rms). Silicon diodes are used in the bridge rectifier circuit of Figure 2-12. Calculate the multiplier resistance value required.

SOLUTION

At FSD, the average current flowing through the PMMC instrument is

$$I_{av} = 100\ \mu\text{A},$$

$$\textit{peak current}\ I_m = \frac{I_{av}}{0.637} = \frac{100\ \mu\text{A}}{0.637} = 157\ \mu\text{A},$$

$$I_m = \frac{\text{(applied peak voltage)} - \text{(rectifier volt drop)}}{\text{total circuit resistance}},$$

$$\textit{rectifier volt drops} = 2V_F\ (\text{for } D_1 \text{ and } D_4 \text{ or } D_2 \text{ and } D_3),$$

$$\textit{applied peak voltage} = 1.414V_{rms},$$

$$\textit{total circuit resistance} = R_s + R_m,$$

$$I_m = \frac{1.414V_{rms} - 2V_F}{R_s + R_m},$$

or

$$R_s = \frac{1.414V_{rms} - 2V_F}{I_m} - R_m$$

$$= \frac{(1.414 \times 100\ \text{V}) - (2 \times 0.7\ \text{V})}{157\ \mu\text{A}} - 1\ \text{k}\Omega$$

$$= 890.7\ \text{k}\Omega.$$

EXAMPLE 2-9 Calculate the pointer indications for the voltmeter in Example 2-8, when the rms input voltage is (a) 75 V and (b) 50 V.

SOLUTION

a. 75 V

$$I_{av} = 0.637 I_m = 0.637\left(\frac{1.414V_{rms} - 2V_F}{R_s + R_m}\right)$$

$$= 0.637\left[\frac{(1.414 \times 75\ \text{V}) - (2 \times 0.7\ \text{V})}{890.7\ \text{k}\Omega + 1\ \text{k}\Omega}\right]$$

$$\simeq 75\ \mu\text{A} = \tfrac{3}{4}\ \text{FSD},$$

b. 50 V

$$I_{av} = 0.637\left[\frac{(1.414 \times 50\ \text{V}) - (2 \times 0.7\ \text{V})}{890.7\ \text{k}\Omega + 1\ \text{k}\Omega}\right]$$

$$\simeq 50\ \mu\text{A} = \tfrac{1}{2}\ \text{FSD}.$$

EXAMPLE 2-10 Calculate the sensitivity of the voltmeter in Example 2-8.

SOLUTION

$$I_m = 157\ \mu\text{A},$$

$$I_{rms} = 0.707 I_m = 0.707 \times 157\ \mu\text{A}$$

$$\simeq 111\ \mu\text{A (at FSD)},$$

$$V_{rms} = 100\ \text{V (at FSD)},$$

$$\text{total } R = \frac{100\ \text{V}}{111\ \mu\text{A}} = 900.9\ \text{k}\Omega,$$

$$\text{sensitivity} = \frac{900.9\ \text{k}\Omega}{100\ \text{V}}\ \Omega/\text{V}$$

$$= 9.009\ \text{k}\Omega/\text{V}$$

$$\simeq 9\ \text{k}\Omega/\text{V}.$$

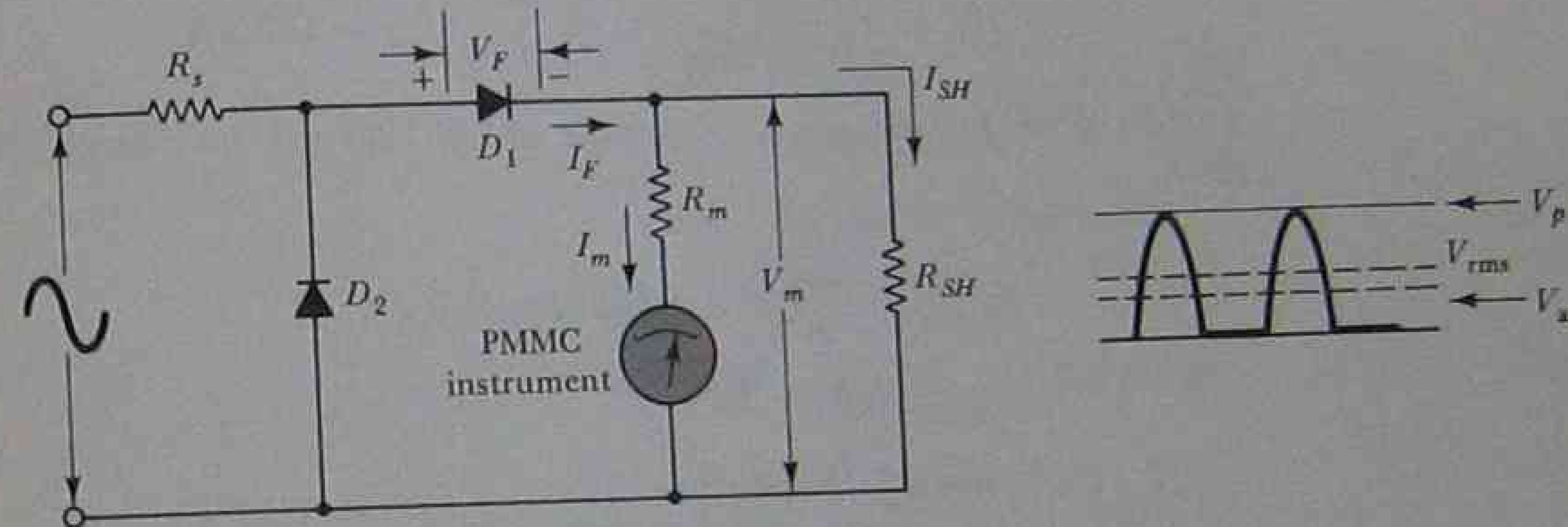
Examples 2-8 and 2-9 demonstrate that the rectifier instrument designed to indicate 100 V rms at full scale, also indicates $\frac{3}{4}$ FSD when 75 V rms is applied, and $\frac{1}{2}$ FSD when 50 V rms is applied. The instrument has a linear scale. At low levels of input voltage, the forward voltage drop across the rectifiers can introduce errors.

A rectifier voltmeter as designed above is for use only on pure sine wave voltages. When other than pure sine waves are applied, the voltmeter will *not* indicate the rms voltage.

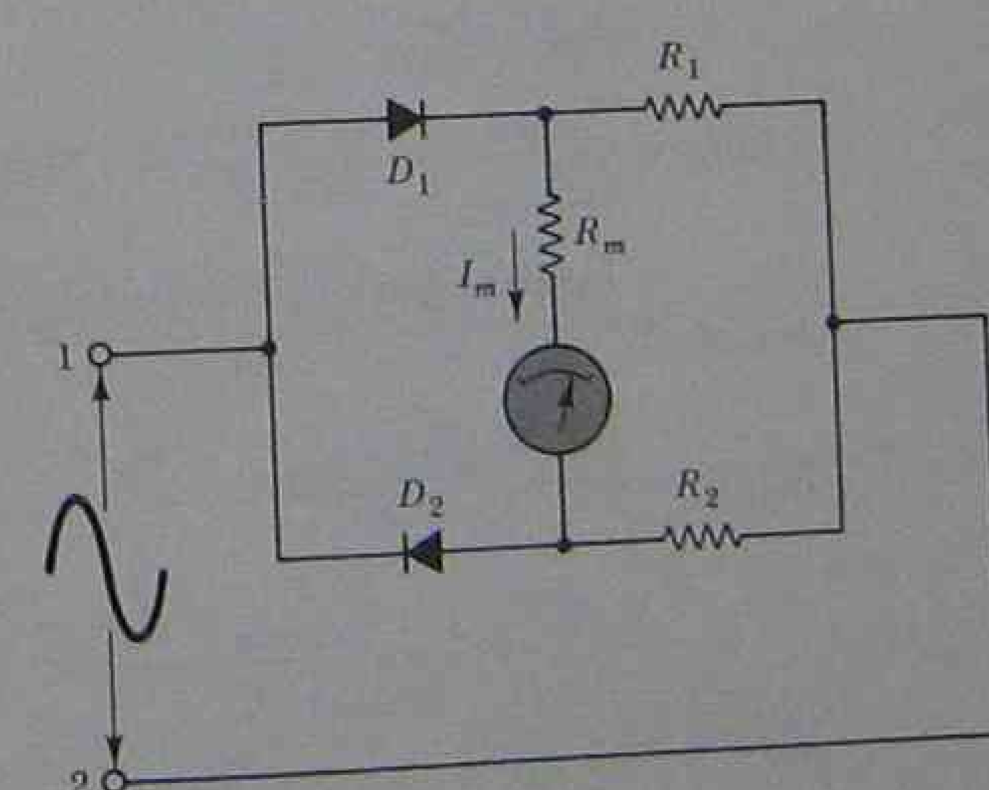
2-3-4 Half-wave Rectifier Voltmeter

Half-wave rectification is employed in the ac voltmeter circuit shown in Figure 2-13(a). R_{SH} shunting the meter is included to cause a relatively large current to flow through diode D_1 (larger than the meter current) when the diode is forward biased. This is to ensure that the diode is biased beyond the knee and well into the linear range of its characteristics [see Figure 2-11(b)]. Diode D_2 conducts during the negative half cycles of the input. When conducting, D_2 causes a very small voltage drop (V_F) across D_1 and the meter, thus preventing the flow of any significant reverse leakage current through the meter via D_1.

The waveform of voltage developed across the meter and R_{SH} is a series of positive half cycles with intervening spaces [Figure 2-13(a)]. In



(a) Voltmeter using half-wave rectifier circuit



(b) Voltmeter using half-bridge full-wave rectifier circuit

FIGURE 2-13. ac voltmeter circuits using half-wave rectification and half-bridge, full-wave rectification.

half-wave rectification, $I_{av} = \frac{1}{2}(0.637\ I_m)$. This must be taken into account in the circuit design calculations.

EXAMPLE 2-11 A PMMC instrument with FSD = 50 μA and R_m = 1700 Ω is used in the half-wave rectifier voltmeter circuit illustrated in Figure 2-13(a). The silicon diode (D_1) must have a minimum forward current of 100 μA when the measured voltage is 20% of FSD. The voltmeter is to indicate 50 V rms at full scale. Calculate the values of R_s and R_{SH}.

SOLUTION

At FSD, $I_{av} = 50\ \mu A$.

Meter peak current,

$$I_m = \frac{I_{av}}{0.5 \times 0.637} = \frac{50\ \mu A}{0.5 \times 0.637} = 157\ \mu A.$$

At 20% of FSD, diode current I_F *must be at least 100 μA; therefore at 100% of* FSD,

$$I_{F(peak)} = \frac{100\%}{20\%} \times 100\ \mu A = 500\ \mu A,$$

$$I_{F(peak)} = I_m + I_{SH},$$

$$I_{SH(peak)} = I_{F(peak)} - I_m$$

$$= 500\ \mu A - 157\ \mu A = 343\ \mu A,$$

$$V_{m(peak)} = I_m R_m = 157\ \mu A \times 1700\ \Omega$$

$$= 266.9\ \text{mV},$$

$$R_{SH} = \frac{V_{m(peak)}}{I_{SH(peak)}} = \frac{266.9\ \text{mV}}{343\ \mu A} = 778\ \Omega,$$

$$I_{F(peak)} = \frac{(\text{applied peak voltage}) - V_{m(peak)} - V_F}{R_s},$$

$$I_{F(peak)} = \frac{1.414 V_{rms} - V_{m(peak)} - V_F}{R_s},$$

$$R_s = \frac{1.414 V_{rms} - V_{m(peak)} - V_F}{I_{F(peak)}}$$

$$= \frac{(1.414 \times 50\ \text{V}) - 266.9\ \text{mV} - 0.7\ \text{V}}{500\ \mu A}$$

$$= 139.5\ \text{k}\Omega.$$

EXAMPLE 2-12 Calculate the sensitivity of the voltmeter in Example 2-11 (a) when D_2 is included in the circuit [see Figure 2-13(a)] and (b) when D_2 is omitted from the circuit.

SOLUTION

a. D_2 in circuit

Peak input current during positive half cycle:

$$I_{F(peak)} = 500\ \mu A.$$

Peak input current during negative half cycle:

$$I_{(peak)} = \frac{1.414\ V_{rms}}{R_s} = \frac{1.414 \times 50\ \text{V}}{139.5\ \text{k}\Omega}$$

$$= 500\ \mu A,$$

$$I_{rms} = 0.707 \times 500\ \mu A$$

$$= 353.5\ \mu A,$$

$$\text{total } R = \frac{50\ \text{V}}{353.5\ \mu A} = 141.4\ \text{k}\Omega,$$

$$\text{sensitivity} = \frac{141.4\ \text{k}\Omega}{50\ \text{V}} = 2.8\ \text{k}\Omega/\text{V}.$$

b. without D_2

Peak input current during positive half cycle:

$$I_{F(peak)} = 500\ \mu A.$$

During negative half cycle:

$$I = 0,$$

$$I_{rms} = 0.5\ I_{F(peak)} \quad \text{(for half-wave rectified)}$$

$$= 0.5 \times 500\ \mu A$$

$$= 250\ \mu A,$$

$$\text{total } R = \frac{50\ \text{V}}{250\ \mu A} = 200\ \text{k}\Omega,$$

$$\text{sensitivity} = \frac{200\ \text{k}\Omega}{50\ \text{V}} = 4\ \text{k}\Omega/\text{V}.$$

2-3-5 Half-bridge Full-wave Rectifier Voltmeter

The circuit in Figure 2-13(b) is that of an ac voltmeter employing a *half-bridge full-wave rectifier circuit*. The *half-bridge* name is applied because two diodes and two resistors are employed, instead of the four diodes used in a full-wave bridge rectifier. This circuit passes full-wave rectified current through the meter, but as in the circuit of Figure 2-13(a), some of the current bypasses the meter.

During the positive half cycle of the input, diode D_1 is forward biased and D_2 is reverse biased. Current flows from terminal 1 through D_1 and the meter (positive to negative), and then through R_2 to terminal 2. But R_1 is in parallel with the meter and R_2, which are connected in series. Therefore, much of the current flowing in D_1 passes through R_1, while only part of it flows through the meter and R_2. During the negative half cycle of the input, D_2 is forward biased and D_1 is reverse biased. Current now flows from terminal 2 through R_1 and the meter, and through D_2 to terminal 1. Now, R_2 is in parallel with the series-connected meter and R_1. Once again, much of the diode current bypasses the meter by flowing through R_2. This arrangement forces the diodes to operate beyond the knee of their characteristics and helps to compensate for differences that might occur in the characteristics of D_1 and D_2.

2-4 RECTIFIER AMMETERS

Like a dc ammeter, an ac ammeter must have a very low resistance because it is always connected in series with the circuit in which current is to be measured. This low resistance requirement means that the voltage drop across the ammeter must be very small, typically not greater than 100 mV. However, the voltage drop across a diode is 0.3 to 0.7 V depending upon whether the diode is made from germanium or silicon. When a bridge rectifier circuit is employed the total diode volt drop is 0.6 to 1.4 V. Clearly, a rectifier instrument is not suitable for direct application as an ac ammeter.

The use of a *current transformer* (Figure 2-14) gives the ammeter a low terminal resistance and low voltage drop. The transformer also steps up the input voltage (more secondary turns than primary turns) to provide sufficient voltage to operate the rectifiers, and at the same time it steps down the primary current to a level suitable for measurement by a PMMC meter. Since the transformer is used in an ammeter circuit, the current transformation ratio $I_p/I_s = N_s/N_p$ is very important.

A precise load resistor (R_L in Figure 2-14) is connected across the secondary winding of the transformer. This is selected to take the portion of secondary current not required by the meter. For example, suppose the PMMC instrument requires 100 μA (average) for FSD, and the current transformer has $N_s = 2000$ and $N_p = 5$. If the rms primary current is 100

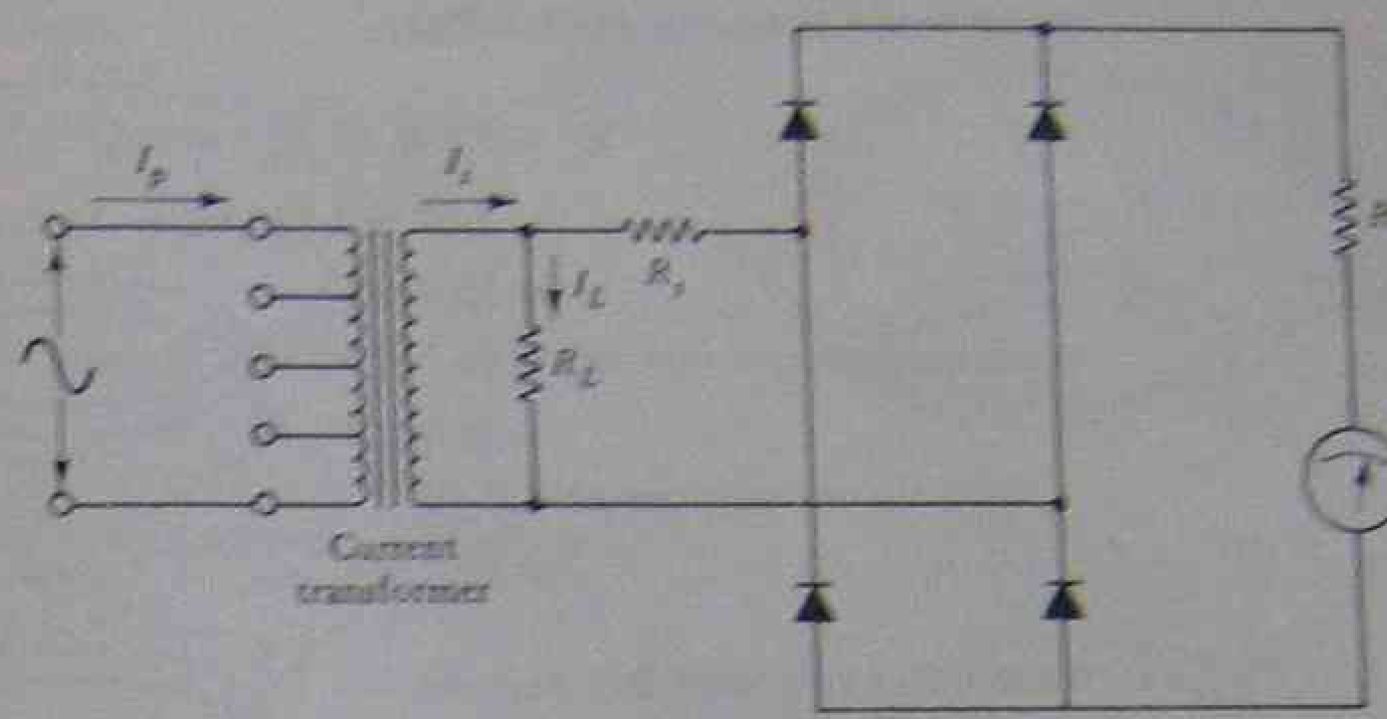


FIGURE 2-14. Rectifier ammeter circuit.

mA, then the secondary rms current is:

$$I_s = \frac{5}{2000} \times 100 \text{ mA} = 250 \ \mu\text{A}$$

or an average of

$$I_{s(av)} = \frac{1}{1.11} \times 250 \ \mu\text{A} = 225.2 \ \mu\text{A}.$$

Since the meter requires 100 μA for FSD, the value of R_L is calculated to pass the remaining 125.2 μA.

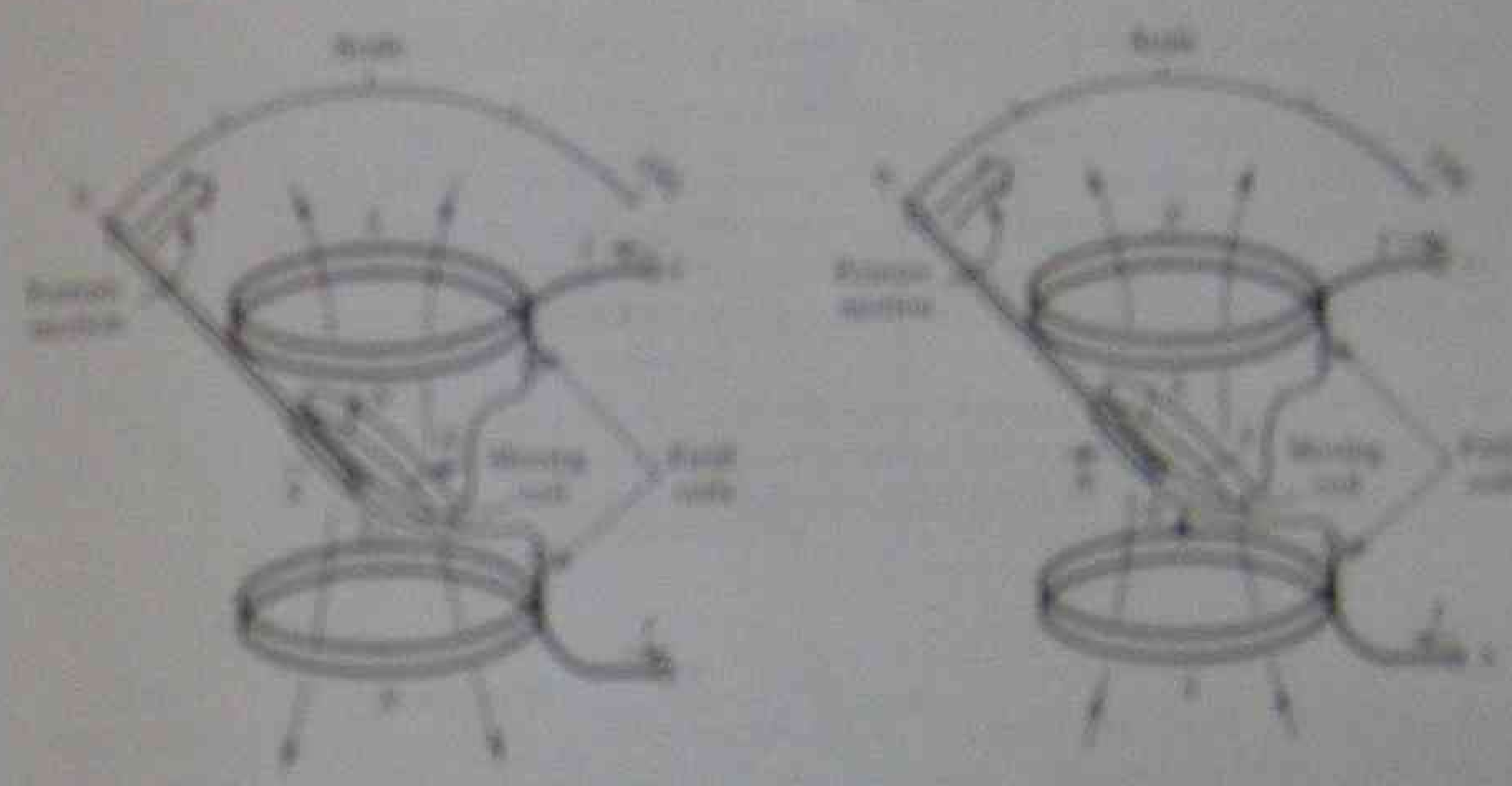
The range of the instrument can be changed by switching-in different values of load resistance. Another method of range changing involves the use of additional terminals (or taps) on the primary winding to alter the number of primary turns. Additional transformer primary terminals are shown in Figure 2-14.

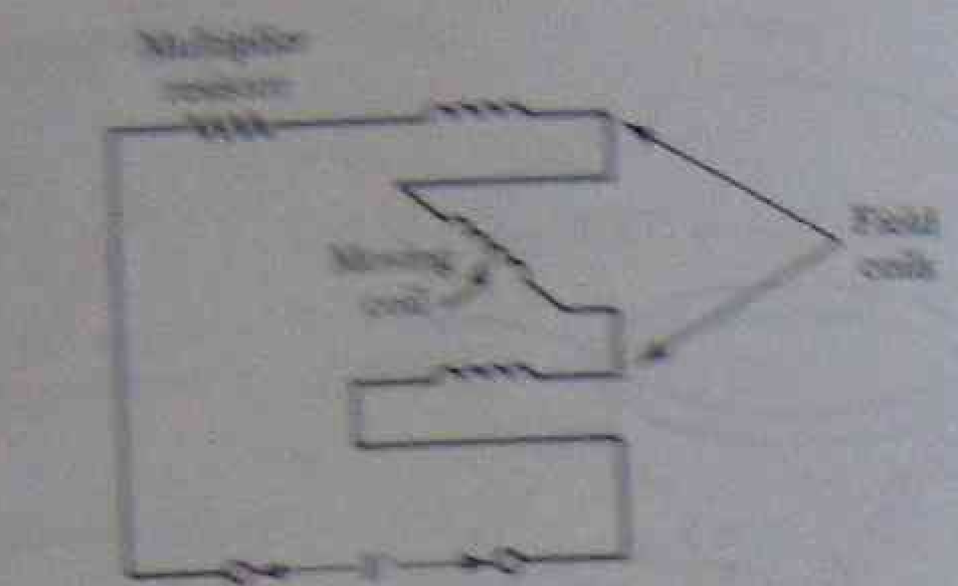
EXAMPLE 2-13

A rectifier ammeter with the circuit shown in Figure 2-14 is to give FSD for a primary current of 250 mA. The PMMC meter has FSD = 1 mA and $R_m = 1700\ \Omega$. The current transformer has $N_s = 500$ and $N_p = 4$. The diodes each have $V_F = 0.7$ V, and the series resistance is $R_s = 20\ \text{k}\Omega$. Calculate the required value of R_L.

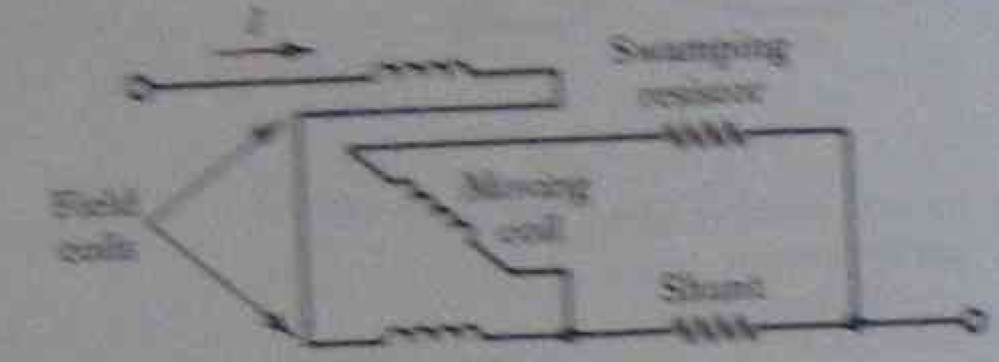
SOLUTION

$$\textit{peak meter current } I_m = \frac{I_{av}}{0.637} = \frac{1 \text{ mA}}{0.637}$$
$$= 1.57 \text{ mA},$$





(a) Electrodynamic voltmeter



(b) Electrodynamic ammeter

FIGURE 2-16. Electrodynamic voltmeter and ammeter circuits.

2-5-2 Electrodynamic Voltmeter

Figure 2-16(a) shows the usual circuit arrangement for an electrodynami voltmeter. Since a voltmeter must have a high resistance, all three coils ar connected in series, and a multiplier resistor (made of manganin o constantan) is included. When the total resistance of the coils, and th required current for FSD are known, the multiplier resistance is calculat exactly as for dc voltmeters. The instrument scale can be read either as d voltage or rms ac voltage. Since it is more convenient to calibrate a instrument on dc than on ac, the electrodynamic voltmeter can be calibrat on dc, and then used either on dc or ac.

Because electrodynamic instruments usually require at least 100 m for FSD, an electrodynamic voltmeter has a much lower sensitivity than PMMC voltmeter. At 100-mA FSD, the sensitivity is 1/100 mA = 1 Ω/V. For a 100-V instrument, this sensitivity gives a total resistance o only 1 kΩ. Therefore, an electrodynamic voltmeter is not suitable fo measuring voltages in electronic circuits because of the loading effect.

2-5-3 Electrodynamic Ammeter

In an electrodynamic ammeter, the moving coil and its series-connecte swamping resistance are connected in parallel with the ammeter shun This is illustrated in Figure 2-16(b). The two field coils should be con

nected in series with the parallel arrangement of shunt and moving coil, as shown.

Because the field coils are always passing the actual current to be measured, resistance changes in the coils with temperature variations have no effect on the instrument performance. However, as in PMMC ammeters, the moving coil must have a manganin or constantan swamping resistance connected in series. Also, the shunt resistor must be made of manganin.

The scale of the electrodynamic ammeter can be read either as dc levels or rms ac values. Like the electrodynamic voltmeter, this instrument can be calibrated on dc and then used to measure either dc or ac.

2-6 ELECTRODYNAMIC WATTMETER

2-6-1 Wattmeter ooperation

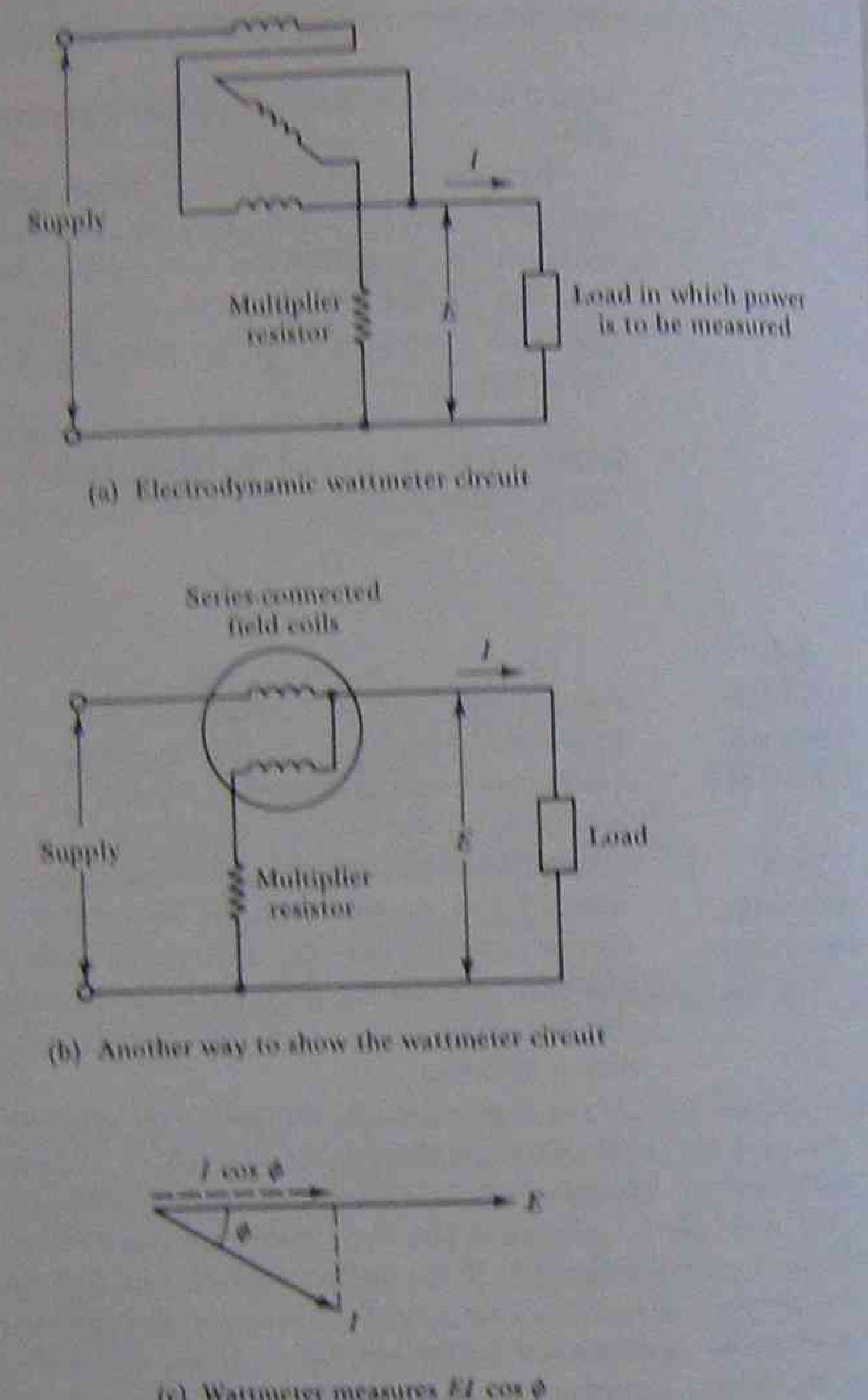
For both dc and ac applications, the most important use of the electrodynamic instrument is as a wattmeter. The coil connections for power measurement are illustrated in Figure 2-17(a). The field coils are connected in series with the load in which power is to be measured so that the load current flows through them. The moving coil and a multiplier resistor are connected in parallel with the load. Thus, the field coils carry the load current, and the moving-coil current is proportional to the load voltage. Since the instrument deflection is proportional to the product of the two currents, deflection = $C \times (EI)$, where C is a constant, or meter indication = EI watts.

In Figure 2-17(b) the electrodynamic wattmeter is shown in a slightly less complicated form than in Figure 2-17(a). A single-coil symbol is used to represent the two series-connected field coils.

Suppose the instrument is correctly connected and giving a positive deflection. If the supply voltage polarity were reversed, the fluxes would reverse in both the field coils and the moving coil. As already explained in Section 2-5, the instrument would still have a positive deflection. In ac circuits where the supply polarity is reversing continuously, the electrodynamic wattmeter gives a positive indication proportional to $E_{rms} I_{rms}$. Like electrodynamic ammeters and voltmeters, the wattmeter can be calibrated on dc and then used to measure power in either dc or ac circuits.

In ac circuits the load current may lead or lag the load voltage by a phase angle ϕ. The wattmeter deflection is proportional to the in-phase components of the current and voltage. As shown in Figure 2-17(c), the instrument deflection is proportional to $EI \cos \phi$. Since the true power dissipated in a load with an ac supply is $EI \cos \phi$, the electrodynamic wattmeter measures true power.

To avoid errors due to changes in the resistance of the moving coil with temperature variations, the multiplier resistor employed in the voltage circuit of a wattmeter must be made of manganin, as in the case of a



(a) Electrodynamic wattmeter circuit

(b) Another way to show the wattmeter circuit

(c) Wattmeter measures $EI \cos \phi$

FIGURE 2-17. Electrodynamic wattmeter circuits and phasor diagram.

voltmeter. Resistance changes in the field coils normally have no effect on the instrument, unless shunts are used in parallel with the coils. When no shunts are used, all of the load current flows through the field coils regardless of the coil resistances.

2-6-2 Compensated Wattmeter

An important source of error in the wattmeter is illustrated in Figure 2-18(a) and (b). Figure 2-18(a) shows that if the moving coil (or voltage coil) circuit is connected in parallel with the load, the field coils pass a current $(I + I_v)$, the sum of the load current and the moving-coil current. This results in the wattmeter indicating the load power (EI), plus a small additional quantity (EI_v). Where the load current is very much larger than I_v, this error may be negligible. In low load current situations, the error may be quite significant.

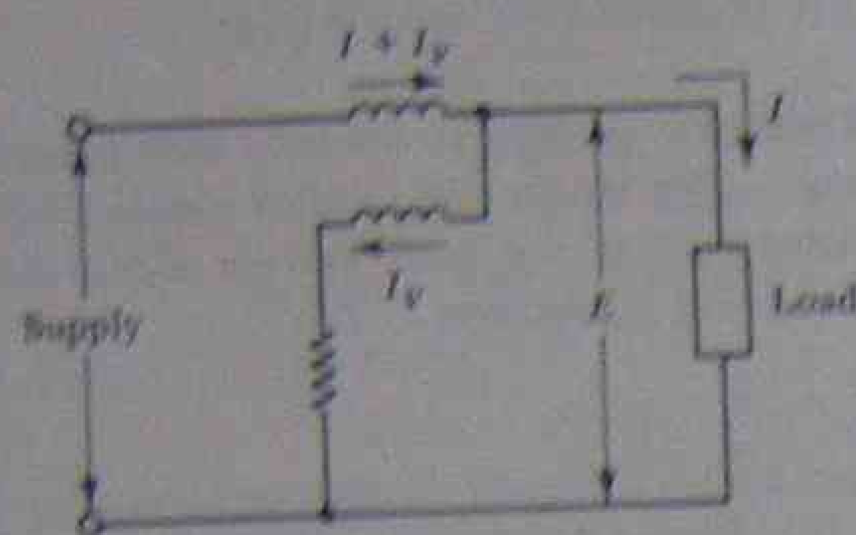
In Figure 2-18(b) the voltage coil is connected to the supply side of the field coils so that only the load current flows through the field coils. However, the voltage applied to the series-connected moving coil and multiplier is $E + E_F$ (the load voltage plus the voltage drop across the field coils). Now the wattmeter indicates load power (EI) plus an additional quantity $(E_F I)$. In high voltage circuits, where the load voltage is very much larger than the voltage drop across the field coils, the error may be insignificant. In low voltage conditions, this error may be serious.

The *compensated wattmeter* illustrated in Figure 2-18(c) eliminates the errors described above. Since the field coils carry the load current, they must be wound of thick copper wire. In the compensated wattmeter, an additional thin conductor is wound right alongside every turn on the field coils. This additional coil, shown broken in Figure 2-17(c), becomes part of the voltage coil circuit. The voltage coil circuit is seen to be connected directly across the load, so that the moving-coil current is always proportional to load voltage. The current through the field coils in $I + I_v$, so that a field coil flux is set up proportional to $I + I_v$. But the additional winding on the field coils carries the moving-coil current I_v, and this sets up a flux in opposition to the main flux of the field coils. The resulting flux in the field coils is $\propto [(I + I_v) - I_v] \propto I$.

Thus the additional winding cancels the field flux due to I_v, and the wattmeter deflection is now directly proportional to EI.

2-6-3 Multirange Wattmeter

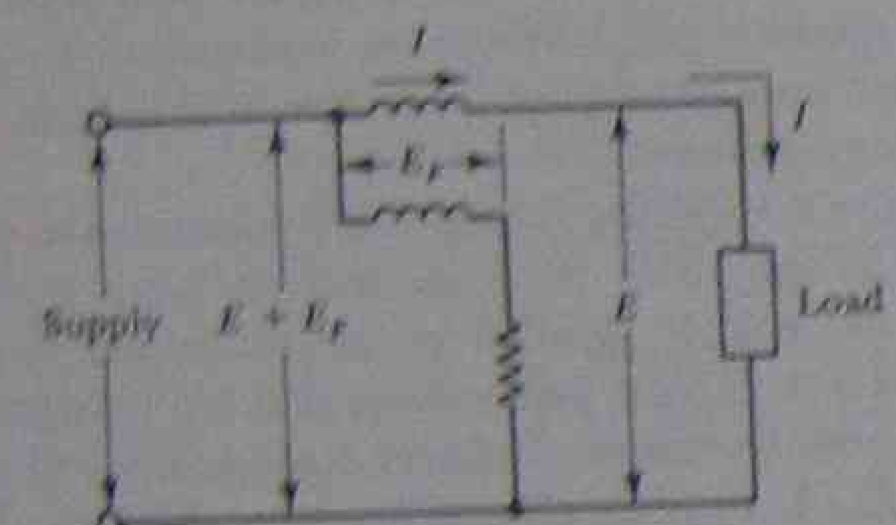
The range of voltages which may be applied to the moving-coil circuit of a wattmeter can be changed by switching different values of multiplier resistors into or out of the circuit, exactly as in the case of a voltmeter. Current range changes can be most easily effected by switching the two field coils from series connection to parallel connection. Figure 2-19 illustrates the circuitry, controls, and scale for a typical multirange wattmeter.



Deflection $\propto E(I + I_V)$

$\propto EI + \underbrace{EI_V}_{\text{Error}}$

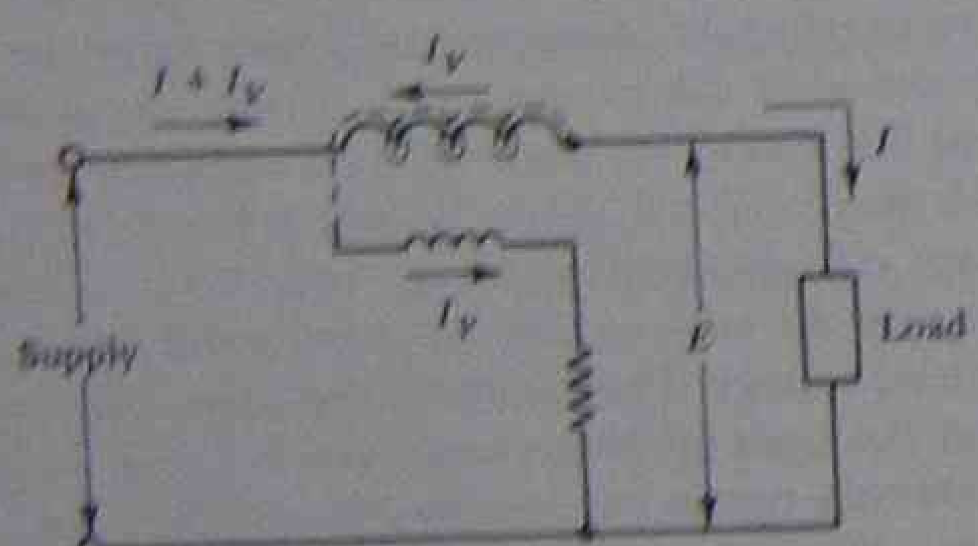
(a) Error due to moving-coil current



Deflection $\propto (E + E_F)I$

$\propto EI + \underbrace{E_F I}_{\text{Error}}$

(b) Error due to field coils voltage drop

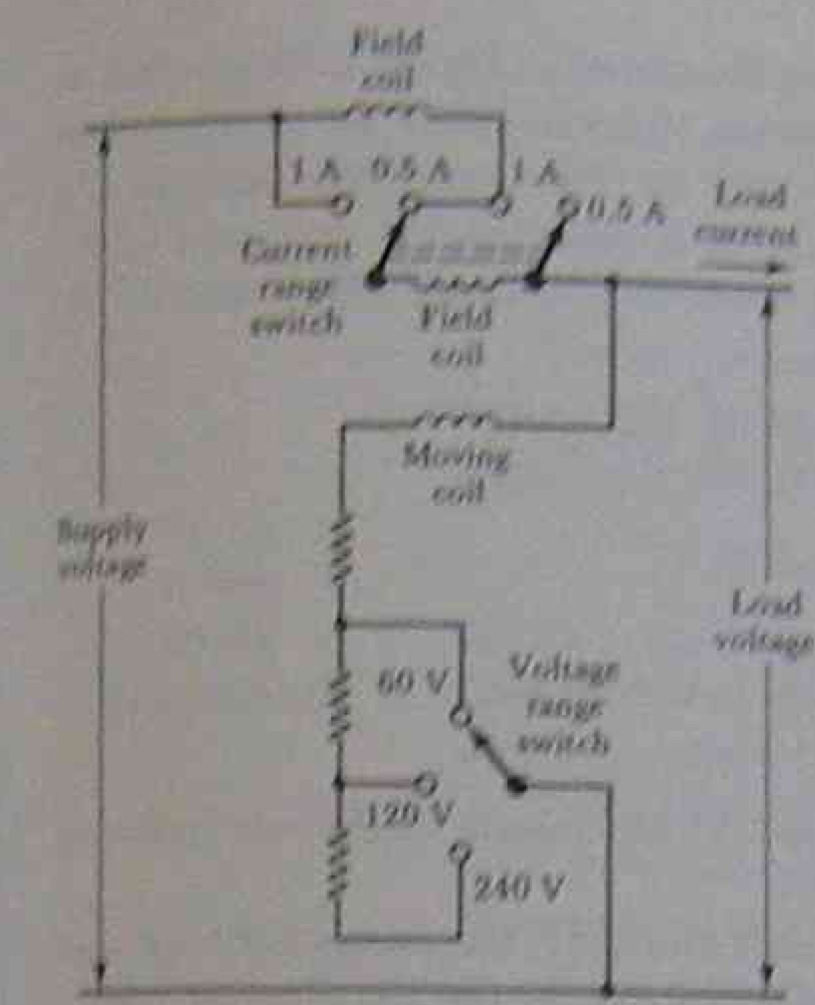


Deflection $\propto E(I + I_V - I_V)$

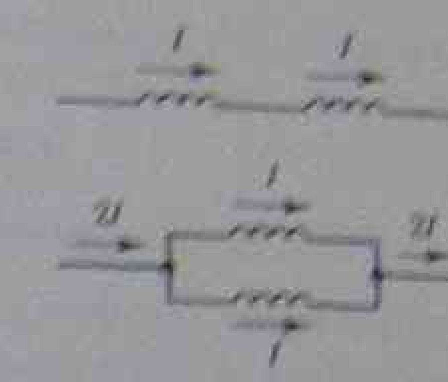
$\propto EI$

(c) Compensated wattmeter using an additional coil wound alongside the field coils

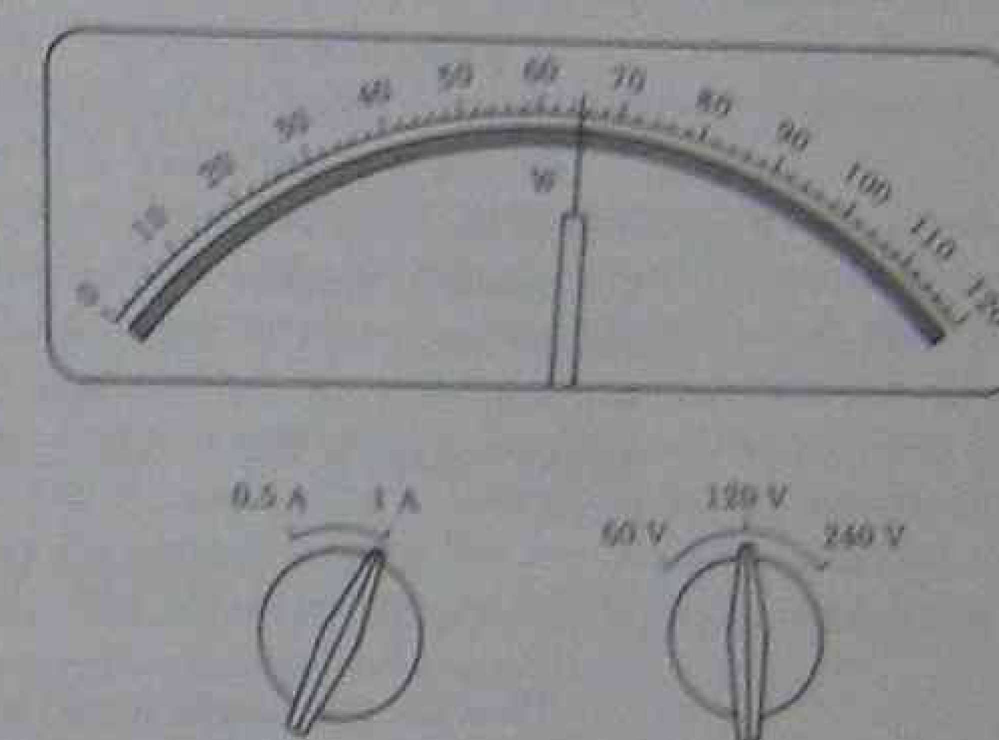
FIGURE 2-18. Wattmeter error sources and the compensated wattmeter.



(a) Circuit of multirange wattmeter



(b) Series-connected and parallel-connected field coils



(c) Wattmeter scale and range controls

FIGURE 2-19. Multirange wattmeter.

In the circuit shown in Figure 2-19(a), the series-connected multiplier resistors give three possible voltage range selections: 60 V, 120 V, and 240 V. The current range switch connects the field coils in series when set to the right, and in parallel when switched left. Figure 2-19(b) shows that if the coils can pass a maximum load current of 0.5 A when connected in series, then when parallel connected the load current can be 1 A. Note that this current (1 A) gives the same deflection as a current of 0.5 A when the field coils were series connected (assuming a constant voltage applied to the moving-coil circuit). However, if the load current is doubled and the load voltage remains constant, then the load power is doubled and the instrument scale reading must be multiplied by a factor of 2.

The wattmeter scale and controls illustrated in Figure 2-19(c) relate to the circuitry in Figure 2-19(a). With the range switches set at 0.5 A and 240 V, the instrument scale reads directly in watts, and FSD indicates 120 W. Similarly, with the 1-A and 120-V ranges selected, the scale may again be read directly in watts. When the range selections are 120 V and 0.5 A,

$$FSD = 120\ V \times 0.5\ A = 60\ W.$$

Also, for a range selection of 1 A and 60 V,

$$FSD = 60\ V \times 1\ A = 60\ W,$$

and for the switch at 0.5 A and 60 V, maximum deflection indicates 0.5 A × 60 V = 30 W.

It is seen that to read the wattmeter correctly, the selected voltage and current ranges must be multiplied together to find the FSD power.

In using a wattmeter it is possible to obtain a reasonable on-scale deflection, while actually overloading either the current or voltage coils. For example, suppose the wattmeter voltage range is set to 60 V and the current range to 1 A. The instrument will have FSD = 60 V × 1 A = 60 W. Now suppose that the actual load current is 0.5 A, and the actual supply voltage is 120 V. The indicated power is

$$P = 120\ V \times 0.5\ A = 60\ W.$$

Thus the instrument would indicate 60 W at full scale, and there is no obvious problem. However, because the voltage circuit has 120 V applied to it, while set at a 60-V range, the moving coil is actually passing twice as much current as it is designed to take. This could cause overheating which may destroy the insulation on the moving coil.

A similar situation could occur with the current coils being overloaded although the wattmeter pointer is indicating on-scale. To avoid such overloads, it is important to know the approximate levels of load voltage and current and to set the instrument ranges accordingly.

The wattmeter scale illustrated in Figure 2-19(c) is linear, although as already explained, electrodynamic voltmeter and ammeter scales are not linear. In the case of the voltmeter, the same current I flows through both the moving coil and field coils so that the instrument deflection is proportional to I^2. With the ammeter, I flows through the field coils, and a portion of I flows in the moving coil. Thus the instrument deflection is again proportional to I^2, and the scale is nonlinear.

With the electrodynamic wattmeter, the moving coil and field coils are supplied independently. Usually, a load in which power is to be measured

has a constant level of supply voltage. When the load current changes, the supply voltage does not change. In this situation, the moving coil carries a constant current proportional to the supply voltage. The instrument deflection is now directly proportional to the load current, and the scale can be calibrated linearly.

Electrodynamic wattmeters are useful for measurement on supply frequencies up to a maximum of 500 Hz. Thus, they are not suitable for high-frequency power measurements.

2-6-4 Using Wattmeters

Before connecting a wattmeter into a circuit, check the mechanical zero of the instrument and adjust it if necessary. While zeroing, tap the instrument gently to relieve bearing friction.

The current circuit of a wattmeter must be connected in series with the load in which power is to be measured. The voltage circuit must be connected in parallel with the load.

If the pointer deflects to the left of zero, either the current terminals or voltage terminals must be reversed.

Before connecting a multirange wattmeter into a circuit, select a voltage range equal to or higher than the supply voltage. Select the highest current range. Then, switch down to the current range which gives the greatest on-scale deflection. Do not adjust the voltage range below the level of the supply voltage. This step ensures that the (low current) voltage coil does not have an excessive current flow. However, it is still possible that excessive current may be passing through the current coils, although the meter is indicating less than full scale. This should also be avoided, but it is less damaging than excessive voltage coil current.

2-7 THERMOCOUPLE INSTRUMENTS

2-7-1 Thermocouples

A junction of two dissimilar metals develops an electromotive force (emf) when heated. By using a current to heat the junction, an emf is produced which is proportional to the heating effect of the current. Since the heating effect of a current is directly proportional to the rms value of the current (no matter what its waveform), the generated emf can be used as a measure of the rms level of the current.

Figure 2-20 illustrates the principle of the *thermocouple instrument*. The thermocouple consists of the junction of two dissimilar metal wires welded to a heating wire. The current to be measured passes through the heater and thus heats the junction. A millivoltmeter measures the voltage developed across the junction. The scale of the meter is calibrated to indicate the actual rms current in the heater.

Two types of thermocouples are illustrated in Figure 2-21. Figure 2-21(a) shows a thermocouple enclosed in a vacuum tube to protect the