Chapter 10

Electrical measuring instruments and measurements

Why it is important to understand: **Electrical measuring instruments and measurements**

Future electrical engineers need to be able to appreciate basic measurement techniques, instruments and methods used in everyday practice. This chapter covers both analogue and digital instruments, measurement errors, bridges, oscilloscopes, data acquisition, instrument controls and measurement systems. Accurate measurements are central to virtually every scientific and engineering discipline. Electrical measurements often come down to either measuring current or measuring voltage. Even if you are measuring frequency, you will be measuring the frequency of a current signal or a voltage signal and you will need to know how to measure either voltage or current. Many times you will use a digital multimeter – a DMM – to measure either voltage or current; actually, a DMM will also usually measure frequency (of a voltage signal) and resistance. The quality of a measuring instrument is assessed from its accuracy, precision, reliability, durability and so on, all of which are related to its cost.

At the end of this chapter you should be able to:

- recognize the importance of testing and measurements in electric circuits
- appreciate the essential devices comprising an analogue instrument
- explain the operation of an attraction and a repulsion type of moving-iron instrument
- explain the operation of a moving coil rectifier instrument
- compare moving coil, moving iron and moving coil rectifier instruments
- calculate values of shunts for ammeters and multipliers for voltmeters
- understand the advantages of electronic instruments
- understand the operation of an ohmmeter/megger
- appreciate the operation of multimeters/Avometers/Flukes
- understand the operation of a wattmeter
- appreciate instrument 'loading' effect

- understand the operation of an oscilloscope for d.c. and a.c. measurements
- calculate periodic time, frequency, peak to peak values from waveforms on an oscilloscope
- appreciate virtual test and measuring instruments
- recognize harmonics present in complex waveforms
- determine ratios of powers, currents and voltages in decibels
- understand null methods of measurement for a Wheatstone bridge and d.c. potentiometer
- understand the operation of a.c. bridges
- appreciate the most likely source of errors in measurements
- appreciate calibration accuracy of instruments

10.1 Introduction

Tests and measurements are important in designing, evaluating, maintaining and servicing electrical circuits and equipment. In order to detect electrical quantities such as current, voltage, resistance or power, it is necessary to transform an electrical quantity or condition into a visible indication. This is done with the aid of instruments (or meters) that indicate the magnitude of quantities either by the position of a pointer moving over a graduated scale (called an analogue instrument) or in the form of a decimal number (called a digital instrument).

The digital instrument has, in the main, become the instrument of choice in recent years; in particular, computer-based instruments are rapidly replacing items of conventional test equipment, with the virtual storage test instrument, the **digital storage oscilloscope**, being the most common. This is explained later in this chapter, but before that some analogue instruments, which are still used in some installations, are explored.

10.2 Analogue instruments

All analogue electrical indicating instruments require three essential devices:

(a) A **deflecting or operating device**. A mechanical force is produced by the current or voltage which causes the pointer to deflect from its zero position.

(b) **A controlling device**. The controlling force acts in opposition to the deflecting force and ensures that the deflection shown on the meter is always the same for a given measured quantity. It also prevents the pointer always going to the maximum deflection. There are two main types of controlling device – spring control and gravity control.

(c) **A damping device**. The damping force ensures that the pointer comes to rest in its final position quickly and without undue oscillation. There are three main types of damping used – eddy-current damping, air-friction damping and fluid-friction damping.

There are basically two types of scale – linear and non-linear.

A **linear scale** is shown in Figure 10.1(a), where the divisions or graduations are evenly spaced. The voltmeter shown has a range 0–100 V, i.e. a full-scale deflection (f.s.d.) of 100 V. A **non-linear scale** is shown in Figure 10.1(b). The scale is cramped at the beginning and the graduations are uneven throughout the range. The ammeter shown has a f.s.d. of 10 A.

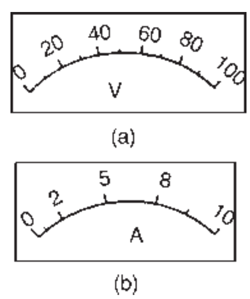

Figure 10.1

10.3 Moving-iron instrument

(a) An **attraction type** of moving-iron instrument is shown diagrammatically in Figure 10.2(a). When current flows in the solenoid, a pivoted soft-iron disc is attracted towards the solenoid and the movement causes a pointer to move across a scale.

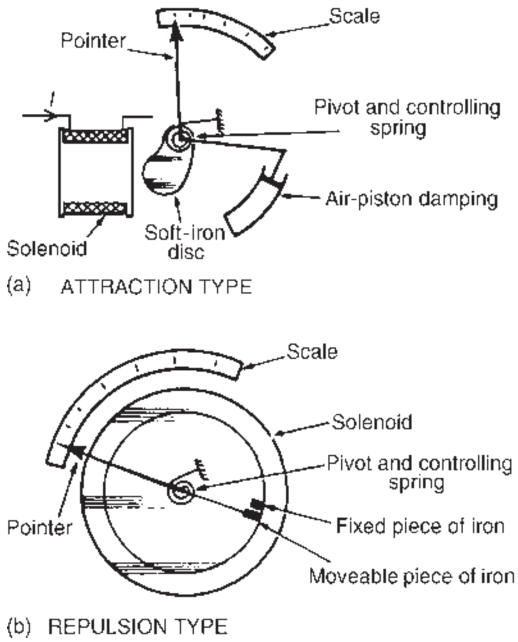

Figure 10.2

(b) In the **repulsion type** moving-iron instrument shown diagrammatically in Figure 10.2(b), two pieces of iron are placed inside the solenoid, one being fixed, and the other attached to the spindle carrying the pointer. When current passes through the solenoid, the two pieces of iron are magnetized in the same direction and therefore repel each other. The pointer thus moves across the scale. The force moving the pointer is, in each type, proportional to I^2. Because of this the direction of current does not matter and the moving-iron instrument can be used on d.c. or a.c. The scale, however, is non-linear.

10.4 The moving-coil rectifier instrument

A moving-coil instrument, which measures only d.c., may be used in conjunction with a bridge rectifier circuit as shown in Figure 10.3 to provide an indication of alternating currents and voltages (see Chapter 14). The average value of the full wave rectified current is $0.637 I_m$. However, a meter being used to measure a.c. is usually calibrated in r.m.s. values. For sinusoidal quantities the indication is $(0.707 I_m)/(0.637 I_m)$ i.e. 1.11 times the mean value. Rectifier instruments have scales calibrated in r.m.s. quantities and it is assumed by the manufacturer that the a.c. is sinusoidal.

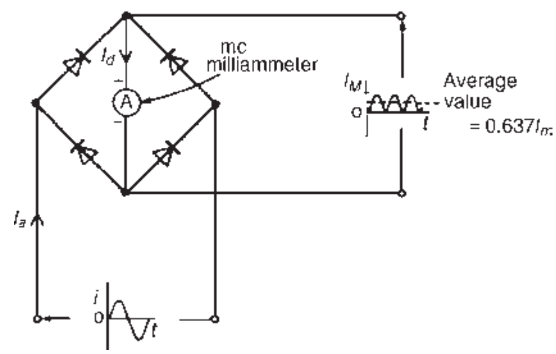

Figure 10.3

10.5 Comparison of moving-coil, moving-iron and moving-coil rectifier instruments

Type of instrument	Moving-coil	Moving-iron	Moving-coil rectifier
Suitable for measuring	Direct current and voltage	Direct and alternating currents and voltage (reading in r.m.s. value)	Alternating current and voltage (reads average value but scale is adjusted to give r.m.s. value for sinusoidal waveforms)
Scale	Linear	Non-linear	Linear
Method of control	Hairsprings	Hairsprings	Hairsprings
Method of damping	Eddy current	Air	Eddy current

(*Continued*)

Type of instrument	Moving-coil	Moving-iron	Moving-coil rectifier
Frequency limits	—	20–200 Hz	20–100 kHz
Advantages	1. Linear scale 2. High sensitivity 3. Well shielded from stray magnetic fields 4. Low power consumption	1. Robust construction 2. Relatively cheap 3. Measures d.c. and a.c. 4. In frequency range 20–100 Hz reads r.m.s. correctly regardless of supply waveform	1. Linear scale 2. High sensitivity 3. Well shielded from stray magnetic fields 4. Lower power consumption 5. Good frequency range
Disadvantages	1. Only suitable for d.c. 2. More expensive than moving-iron type 3. Easily damaged	1. Non-linear scale 2. Affected by stray magnetic fields 3. Hysteresis errors in d.c. circuits 4. Liable to temperature errors 5. Due to the inductance of the solenoid, readings can be affected by variation of frequency	1. More expensive than moving-iron type 2. Errors caused when supply is non-sinusoidal

(For the principle of operation of a moving-coil instrument, see Chapter 8, page 89).

10.6 Shunts and multipliers

An **ammeter**, which measures current, has a low resistance (ideally zero) and must be connected in series with the circuit.

A **voltmeter**, which measures p.d., has a high resistance (ideally infinite) and must be connected in parallel with the part of the circuit whose p.d. is required.

There is no difference between the basic instrument used to measure current and voltage since both use a milliammeter as their basic part. This is a sensitive instrument which gives f.s.d. for currents of only a few milliamperes. When an ammeter is required to measure currents of larger magnitude, a proportion of the current is diverted through a low-value resistance connected in parallel with the meter. Such a diverting resistor is called a **shunt**.

From Figure 10.4(a), $V_{PQ} = V_{RS}$. Hence $I_a r_a = I_S R_S$

Thus the value of the shunt, $\boldsymbol{R_s = \frac{I_a r_a}{I_s}}$ **ohms**

The milliammeter is converted into a voltmeter by connecting a high-value resistance (called a **multiplier**) in series with it, as shown in Figure 10.4(b). From Figure 10.4(b), $V = V_a + V_M = Ir_a + IR_M$

Thus the value of the multiplier, $\boldsymbol{R_M = \frac{V - Ir_a}{I}}$ **ohms**

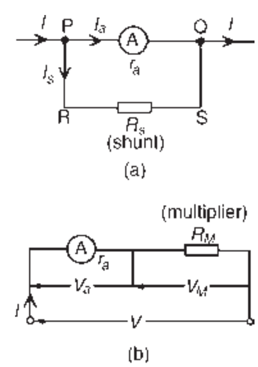

Figure 10.4

Problem 1. A moving-coil instrument gives an f.s.d. when the current is 40 mA and its resistance is 25 Ω. Calculate the value of the shunt to be connected in parallel with the meter to enable it to be used as an ammeter for measuring currents up to 50 A.

The circuit diagram is shown in Figure 10.5,

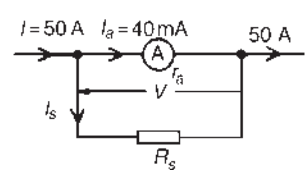

Figure 10.5

where r_a = resistance of instrument = 25 Ω,

R_s = resistance of shunt,

I_a = maximum permissible current flowing in instrument = 40 mA = 0.04 A,

I_s = current flowing in shunt,

I = total circuit current required to give f.s.d. = 50 A

Since $I = I_a + I_s$ then $I_s = I - I_a = 50 - 0.04$

$= 49.96\,\text{A}$

$$V = I_a r_a = I_s R_s$$

Hence $R_s = \dfrac{I_a r_a}{I_s} = \dfrac{(0.04)(25)}{49.96} = 0.02002\,\Omega$

$= \mathbf{20.02\,m\Omega}$

Thus for the moving-coil instrument to be used as an ammeter with a range 0–50 A, a resistance of value 20.02 mΩ needs to be connected in parallel with the instrument.

Problem 2. A moving-coil instrument having a resistance of 10 Ω gives an f.s.d. when the current is 8 mA. Calculate the value of the multiplier to be connected in series with the instrument so that it can be used as a voltmeter for measuring p.d.s up to 100 V.

The circuit diagram is shown in Figure 10.6,

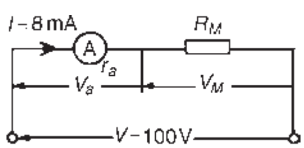

Figure 10.6

where r_a = resistance of instrument = 10 Ω,

R_M = resistance of multiplier,

I = total permissible instrument current = 8 mA = 0.008 A,

V = total p.d. required to give f.s.d. = 100 V

$$V = V_a + V_M = I r_a + I R_M$$

i.e. $100 = (0.008)(10) + (0.008)\,R_M$

or $100 - 0.08 = 0.008\,R_M$

thus $R_M = \dfrac{99.92}{0.008} = 12\,490\,\Omega = \mathbf{12.49\,k\Omega}$

Hence for the moving-coil instrument to be used as a voltmeter with a range 0–100 V, a resistance of value 12.49 kΩ needs to be connected in series with the instrument.

Now try the following Practice Exercise

Practice Exercise 32 Shunts and multipliers (Answers on page 745)

1. A moving-coil instrument gives f.s.d. for a current of 10 mA. Neglecting the resistance of the instrument, calculate the approximate value of series resistance needed to enable the instrument to measure up to (a) 20 V, (b) 100 V, (c) 250 V.
2. A meter of resistance 50 Ω has an f.s.d. of 4 mA. Determine the value of shunt resistance required in order that f.s.d. should be (a) 15 mA, (b) 20 A, (c) 100 A.
3. A moving-coil instrument having a resistance of 20 Ω gives an f.s.d. when the current is 5 mA. Calculate the value of the multiplier to be connected in series with the instrument so that it can be used as a voltmeter for measuring p.d.s up to 200 V.
4. A moving-coil instrument has a f.s.d. of 20 mA and a resistance of 25 Ω. Calculate the values of resistance required to enable the instrument to be used (a) as a 0–10 A ammeter, and (b) as a 0–100 V voltmeter. State the mode of resistance connection in each case.

10.7 Electronic instruments

Electronic measuring instruments have advantages over instruments such as the moving-iron or moving-coil meters, in that they have a much higher input resistance (some as high as 1000 MΩ) and can handle a much wider range of frequency (from d.c. up to MHz).

The digital voltmeter (DVM) is one which provides a digital display of the voltage being measured. Advantages of a DVM over analogue instruments include higher accuracy and resolution, no observational or parallax errors (see Section 10.21) and a very high input resistance, constant on all ranges.

A digital multimeter is a DVM with additional circuitry which makes it capable of measuring a.c. voltage, d.c. and a.c. current and resistance.

Instruments for a.c. measurements are generally calibrated with a sinusoidal alternating waveform to indicate r.m.s. values when a sinusoidal signal is applied to the instrument. Some instruments, such as the moving-iron and electro-dynamic instruments, give a true r.m.s. indication. With other instruments the indication is either scaled up from the mean value (such as with the rectifier moving-coil instrument) or scaled down from the peak value.

Sometimes quantities to be measured have complex waveforms (see Section 10.15), and whenever a quantity is non-sinusoidal, errors in instrument readings can occur if the instrument has been calibrated for sine waves only.

Such waveform errors can be largely eliminated by using electronic instruments.

10.8 The ohmmeter

An **ohmmeter** is an instrument for measuring electrical resistance.

A simple ohmmeter circuit is shown in Figure 10.7(a). Unlike the ammeter or voltmeter, the ohmmeter circuit does not receive the energy necessary for its operation from the circuit under test. In the ohmmeter this energy is supplied by a self-contained source of voltage, such as a battery. Initially, terminals XX are short-circuited and R adjusted to give f.s.d. on the milliammeter. If current I is at a maximum value and voltage E is constant, then resistance $R = E/I$ is at a minimum value. Thus f.s.d. on the milliammeter is made zero on the resistance scale. When terminals XX are open circuited no current flows and $R(= E/O)$ is infinity, ∞.

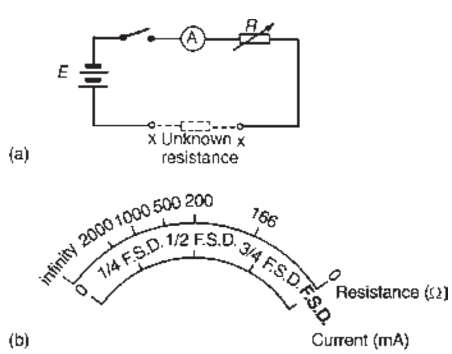

Figure 10.7

The milliammeter can thus be calibrated directly in ohms. A cramped (non-linear) scale results and is 'back to front', as shown in Figure 10.7(b). When calibrated, an unknown resistance is placed between terminals XX and its value determined from the position of the pointer on the scale. An ohmmeter designed for measuring low values of resistance is called a **continuity tester**. An ohmmeter designed for measuring high values of resistance (i.e. megohms) is called an **insulation resistance tester** (e.g. **'Megger'**).

10.9 Multimeters

Instruments are manufactured that combine a moving-coil meter with a number of shunts and series multipliers, to provide a range of readings on a single scale graduated to read current and voltage. If a battery is incorporated then resistance can also be measured. Such instruments are called **multimeters** or **universal instruments** or **multirange instruments**. An 'Avometer' is a typical example. A particular range may be selected either by the use of separate terminals or by a selector switch. Only one measurement can be performed at a time. Often such instruments can be used in a.c. as well as d.c. circuits when a rectifier is incorporated in the instrument.

Digital multimeters (DMM) are now almost universally used, the **Fluke Digital Multimeter** being an industry leader for performance, accuracy, resolution, ruggedness, reliability and safety. These instruments measure d.c. currents and voltages, resistance and continuity, a.c. (r.m.s.) currents and voltages, temperature and much more.

10.10 Wattmeters

A **wattmeter** is an instrument for measuring electrical power in a circuit. Figure 10.8 shows typical connections of a wattmeter used for measuring power supplied to a load. The instrument has two coils:

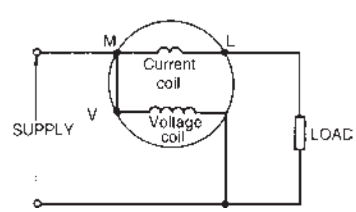

Figure 10.8

(i) a current coil, which is connected in series with the load, like an ammeter, and

(ii) a voltage coil, which is connected in parallel with the load, like a voltmeter.

10.11 Instrument 'loading' effect

Some measuring instruments depend for their operation on power taken from the circuit in which measurements are being made. Depending on the 'loading' effect of the instrument (i.e. the current taken to enable it to operate), the prevailing circuit conditions may change.

The resistance of voltmeters may be calculated since each have a stated sensitivity (or 'figure of merit'), often stated in 'kΩ per volt' of f.s.d. A voltmeter should have as high a resistance as possible – ideally infinite.

In a.c. circuits the impedance of the instrument varies with frequency and thus the loading effect of the instrument can change.

Problem 3. Calculate the power dissipated by the voltmeter and by resistor R in Figure 10.9 when (a) $R = 250\,\Omega$, (b) $R = 2\,\text{M}\Omega$. Assume that the voltmeter sensitivity (sometimes called figure of merit) is $10\,\text{k}\Omega/\text{V}$.

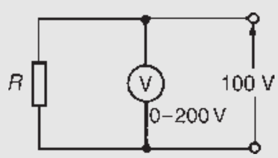

Figure 10.9

(a) Resistance of voltmeter, R_v = sensitivity × f.s.d.

Hence, $R_v = (10\,\text{k}\Omega/\text{V}) \times (200\,\text{V}) = 2000\,\text{k}\Omega$

$= 2\,\text{M}\Omega$

Current flowing in voltmeter, $I_v = \dfrac{V}{R_v} = \dfrac{100}{2 \times 10^6}$

$= 50 \times 10^{-6}\,\text{A}$

Power dissipated by voltmeter $= VI_v$

$= (100)(50 \times 10^{-6})$

$= \mathbf{5\,mW}$

When $R = 250\,\Omega$, current in resistor, $I_R = \dfrac{V}{R}$

$= \dfrac{100}{250} = \mathbf{0.4\,A}$

Power dissipated in load resistor $R = VI_R$

$= (100)(0.4) = \mathbf{40\,W}$

Thus the power dissipated in the voltmeter is insignificant in comparison with the power dissipated in the load.

(b) When $R = 2\,\text{M}\Omega$, current in resistor,

$I_R = \dfrac{V}{R} = \dfrac{100}{2 \times 10^6} = 50 \times 10^{-6}\,\text{A}$

Power dissipated in load resistor

$R = VI_R = 100 \times 50 \times 10^{-6} = \mathbf{5\,mW}$

In this case the higher load resistance reduced the power dissipated such that the voltmeter is using as much power as the load.

Problem 4. An ammeter has an f.s.d. of 100 mA and a resistance of 50 Ω. The ammeter is used to measure the current in a load of resistance 500 Ω when the supply voltage is 10 V. Calculate (a) the ammeter reading expected (neglecting its resistance), (b) the actual current in the circuit, (c) the power dissipated in the ammeter and (d) the power dissipated in the load.

From Figure 10.10,

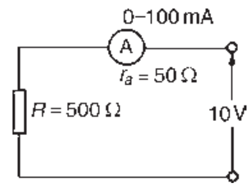

Figure 10.10

(a) expected ammeter reading $= \dfrac{V}{R} = \dfrac{10}{500} = \mathbf{20\,mA}$

(b) Actual ammeter reading $= \dfrac{V}{R + r_a} = \dfrac{10}{500 + 50}$

$= \mathbf{18.18\,mA}$

Thus the ammeter itself has caused the circuit conditions to change from 20 mA to 18.18 mA

(c) Power dissipated in the ammeter
$= I^2 r_a = (18.18 \times 10^{-3})^2(50) = \mathbf{16.53\,mW}$

(d) Power dissipated in the load resistor
$= I^2 R = (18.18 \times 10^{-3})^2(500) = \mathbf{165.3\,mW}$

Problem 5. A voltmeter having an f.s.d. of 100 V and a sensitivity of 1.6 kΩ/V is used to measure voltage V_1 in the circuit of Figure 10.11. Determine (a) the value of voltage V_1 with the voltmeter not connected, and (b) the voltage indicated by the voltmeter when connected between A and B.

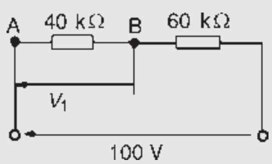

Figure 10.11

(a) By voltage division, $V_1 = \left(\dfrac{40}{40+60}\right)100 = \mathbf{40\,V}$

(b) The resistance of a voltmeter having a 100 V f.s.d. and sensitivity 1.6 kΩ/V is 100 V × 1.6 kΩ/V = 160 kΩ.
When the voltmeter is connected across the 40 kΩ resistor the circuit is as shown in Figure 10.12(a) and the equivalent resistance of the parallel network is given by

$$\left(\frac{40 \times 160}{40+160}\right)\text{k}\Omega \quad \text{i.e.} \quad \left(\frac{40 \times 160}{200}\right)\Omega = 32\,\text{k}\Omega$$

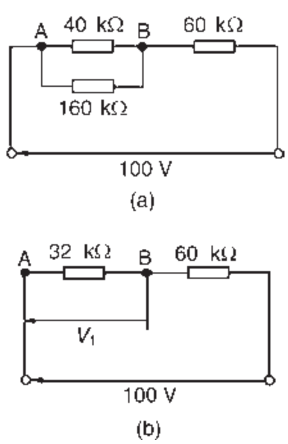

Figure 10.12

The circuit is now effectively as shown in Figure 10.12(b).
Thus the voltage indicated on the voltmeter is

$$\left(\frac{32}{32+60}\right)100\,\text{V} = \mathbf{34.78\,V}$$

A considerable error is thus caused by the loading effect of the voltmeter on the circuit. The error is reduced by using a voltmeter with a higher sensitivity.

Problem 6. (a) A current of 20 A flows through a load having a resistance of 2 Ω. Determine the power dissipated in the load. (b) A wattmeter, whose current coil has a resistance of 0.01 Ω, is connected as shown in Figure 10.13. Determine the wattmeter reading.

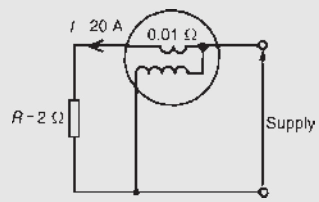

Figure 10.13

(a) Power dissipated in the load, $P = I^2 R = (20)^2(2)$
$= \mathbf{800\,W}$

(b) With the wattmeter connected in the circuit the total resistance R_T is $2 + 0.01 = 2.01\,\Omega$

The wattmeter reading is thus $I^2 R_T = (20)^2(2.01)$
$= \mathbf{804\,W}$

Now try the following Practice Exercise

Practice Exercise 33 Instrument 'loading' effects (Answers on page 745)

1. A 0–1 A ammeter having a resistance of 50 Ω is used to measure the current flowing in a 1 kΩ resistor when the supply voltage is 250 V. Calculate: (a) the approximate value of current (neglecting the ammeter resistance), (b) the actual current in the circuit, (c) the power dissipated in the ammeter, (d) the power dissipated in the 1 kΩ resistor.

2. (a) A current of 15 A flows through a load having a resistance of 4 Ω. Determine the power dissipated in the load. (b) A wattmeter,

whose current coil has a resistance of 0.02 Ω, is connected (as shown in Figure 10.13) to measure the power in the load. Determine the wattmeter reading assuming the current in the load is still 15 A.

3. A voltage of 240 V is applied to a circuit consisting of an 800 Ω resistor in series with a 1.6 kΩ resistor. What is the voltage across the 1.6 kΩ resistor? The p.d. across the 1.6 kΩ resistor is measured by a voltmeter of f.s.d. 250 V and sensitivity 100 Ω/V. Determine the voltage indicated.

4. A 240 V supply is connected across a load of resistance R. Also connected across R is a voltmeter having an f.s.d. of 300 V and a figure of merit (i.e. sensitivity) of 8 kΩ/V. Calculate the power dissipated by the voltmeter and by the load resistance if (a) $R = 100\,\Omega$ (b) $R = 1\,\text{M}\Omega$. Comment on the results obtained.

10.12 The oscilloscope

The oscilloscope is basically a graph-displaying device – it draws a graph of an electrical signal. In most applications the graph shows how signals change over time. From the graph it is possible to:

- determine the time and voltage values of a signal
- calculate the frequency of an oscillating signal
- see the 'moving parts' of a circuit represented by the signal
- tell if a malfunctioning component is distorting the signal
- find out how much of a signal is d.c. or a.c.
- tell how much of the signal is noise and whether the noise is changing with time

Oscilloscopes are used by everyone from television repair technicians to physicists. They are indispensable for anyone designing or repairing electronic equipment. The usefulness of an oscilloscope is not limited to the world of electronics. With the proper transducer (i.e. a device that creates an electrical signal in response to physical stimuli, such as sound, mechanical stress, pressure, light or heat), an oscilloscope can measure any kind of phenomena. An automobile engineer uses an oscilloscope to measure engine vibrations; a medical researcher uses an oscilloscope to measure brain waves, and so on.

Oscilloscopes are available in both analogue and digital types. An **analogue oscilloscope** works by directly applying a voltage being measured to an electron beam moving across the oscilloscope screen. The voltage deflects the beam up or down proportionally, tracing the waveform on the screen. This gives an immediate picture of the waveform.

In contrast, a **digital oscilloscope** samples the waveform and uses an analogue-to-digital converter (see Section 18.11, page 264) to convert the voltage being measured into digital information. It then uses this digital information to reconstruct the waveform on the screen.

For many applications either an analogue or digital oscilloscope is appropriate. However, each type does possess some unique characteristics making it more or less suitable for specific tasks.

Analogue oscilloscopes are often preferred when it is important to display rapidly varying signals in 'real time' (i.e. as they occur).

Digital oscilloscopes allow the capture and viewing of events that happen only once. They can process the digital waveform data or send the data to a computer for processing. Also, they can store the digital waveform data for later viewing and printing. Digital storage oscilloscopes are explained in Section 10.14.

Analogue oscilloscopes

When an oscilloscope probe is connected to a circuit, the voltage signal travels through the probe to the vertical system of the oscilloscope. Figure 10.14 shows a simple block diagram that shows how an analogue oscilloscope displays a measured signal.

Depending on how the vertical scale (volts/division control) is set, an attenuator reduces the signal voltage or an amplifier increases the signal voltage. Next, the signal travels directly to the vertical deflection plates of the cathode ray tube (CRT). Voltage applied to these deflection plates causes a glowing dot to move. (An electron beam hitting phosphor inside the CRT creates the glowing dot.) A positive voltage causes the dot to move up while a negative voltage causes the dot to move down. The signal also travels to the trigger system to start or trigger a 'horizontal sweep'. Horizontal sweep is a term referring to the action of the horizontal system causing the glowing dot to move across the screen. Triggering the horizontal system causes the horizontal time base to move the glowing dot across the screen from left to right within a specific time interval. Many sweeps

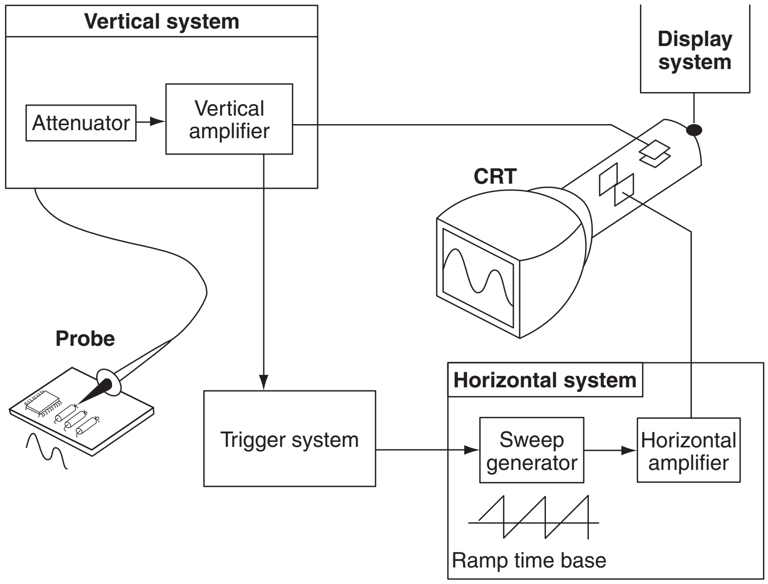

Figure 10.14

in rapid sequence cause the movement of the glowing dot to blend into a solid line. At higher speeds, the dot may sweep across the screen up to 500 000 times each second.

Together, the horizontal sweeping action (i.e. the X direction) and the vertical deflection action (i.e. the Y direction), trace a graph of the signal on the screen. The trigger is necessary to stabilize a repeating signal. It ensures that the sweep begins at the same point of a repeating signal, resulting in a clear picture.

In conclusion, to use an analogue oscilloscope, three basic settings to accommodate an incoming signal need to be adjusted:

- the attenuation or amplification of the signal – use the volts/division control to adjust the amplitude of the signal before it is applied to the vertical deflection plates
- the time base – use the time/division control to set the amount of time per division represented horizontally across the screen
- the triggering of the oscilloscope – use the trigger level to stabilize a repeating signal, as well as triggering on a single event.

Also, adjusting the focus and intensity controls enable a sharp, visible display to be created.

(i) With **direct voltage measurements**, only the Y amplifier 'volts/cm' switch on the oscilloscope is used. With no voltage applied to the Y plates the position of the spot trace on the screen is noted. When a direct voltage is applied to the Y plates the new position of the spot trace is an indication of the magnitude of the voltage. For example, in Figure 10.15(a), with no voltage applied to the Y plates, the spot trace is in the centre of the screen (initial position) and then the spot trace moves 2.5 cm to the final position shown, on application of a d.c. voltage. With the 'volts/cm' switch on 10 volts/cm the magnitude of the direct voltage is 2.5 cm × 10 volts/cm, i.e. 25 volts.

(ii) With **alternating voltage measurements**, let a sinusoidal waveform be displayed on an oscilloscope screen as shown in Figure 10.15(b). If the time/cm switch is on, say, 5 ms/cm then the **periodic time *T*** of the sinewave is 5 ms/cm × 4 cm, i.e. **20 ms** or **0.02 s**

Since frequency $f = \frac{1}{T}$, $\textbf{frequency} = \frac{\mathbf{1}}{\mathbf{0.02}} = \mathbf{50\,Hz}$

If the 'volts/cm' switch is on, say, 20 volts/cm then the **amplitude** or **peak value** of the sinewave shown is 20 volts/cm × 2 cm, i.e. 40 V.

Since r.m.s. voltage $= \frac{\text{peak voltage}}{\sqrt{2}}$,

(see Chapter 14),

$$\textbf{r.m.s. voltage} = \frac{40}{\sqrt{2}} = \mathbf{28.28\ volts}$$

Double beam oscilloscopes are useful whenever two signals are to be compared simultaneously.

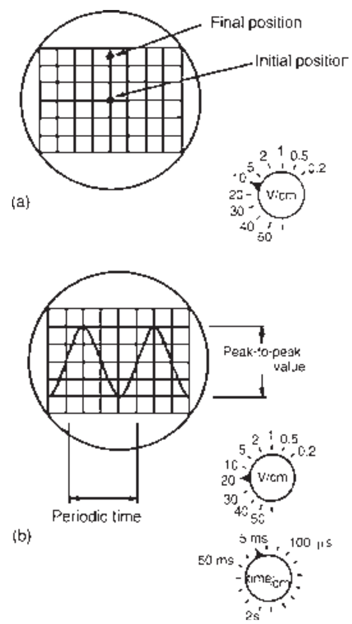

Figure 10.15

The oscilloscope demands reasonable skill in adjustment and use. However, its greatest advantage is in observing the shape of a waveform – a feature not possessed by other measuring instruments.

Digital oscilloscopes

Some of the systems that make up digital oscilloscopes are the same as those in analogue oscilloscopes; however, digital oscilloscopes contain additional data processing systems – as shown in the block diagram of Figure 10.16. With the added systems, the digital oscilloscope collects data for the entire waveform and then displays it.

When a digital oscilloscope probe is attached to a circuit, the vertical system adjusts the amplitude of the signal, just as in the analogue oscilloscope. Next, the analogue-to-digital converter (ADC) in the acquisition system samples the signal at discrete points in time and converts the signals' voltage at these points to digital values called *sample points*. The horizontal systems' sample clock determines how often the ADC takes a sample. The rate at which the clock 'ticks' is called the sample rate and is measured in samples per second.

The sample points from the ADC are stored in memory as *waveform points*. More than one sample point may make up one waveform point.

Together, the waveform points make up one waveform *record*. The number of waveform points used to make a waveform record is called a *record length*. The trigger system determines the start and stop points of the record. The display receives these record points after being stored in memory.

Depending on the capabilities of an oscilloscope, additional processing of the sample points may take place, enhancing the display. Pre-trigger may be available, allowing events to be seen before the trigger point.

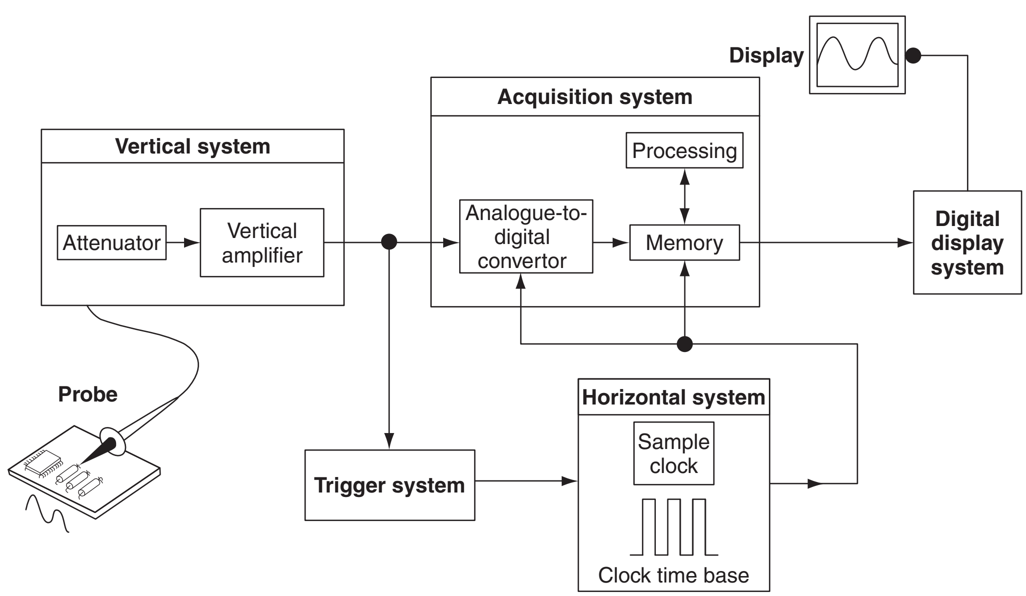

Figure 10.16

Fundamentally, with a digital oscilloscope as with an analogue oscilloscope, there is a need to adjust vertical, horizontal and trigger settings to take a measurement.

Problem 7. For the oscilloscope square voltage waveform shown in Figure 10.17, determine (a) the periodic time, (b) the frequency and (c) the peak-to-peak voltage. The 'time/cm' (or timebase control) switch is on 100 μs/cm and the 'volts/cm' (or signal amplitude control) switch is on 20 V/cm.

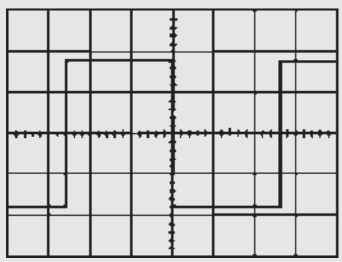

Figure 10.17

(In Figures 10.17 to 10.20 assume that the squares shown are 1 cm by 1 cm.)

(a) The width of one complete cycle is 5.2 cm

Hence the periodic time,
$T = 5.2\,\text{cm} \times 100 \times 10^{-6}\,\text{s/cm} = \mathbf{0.52\,ms}$

(b) Frequency, $f = \frac{1}{T} = \frac{1}{0.52 \times 10^{-3}} = \mathbf{1.92\,kHz}$

(c) The peak-to-peak height of the display is 3.6 cm, hence the peak-to-peak voltage $= 3.6\,\text{cm} \times 20\,\text{V/cm}$
$= \mathbf{72\,V}$

Problem 8. For the oscilloscope display of a pulse waveform shown in Figure 10.18 the 'time/cm' switch is on 50 ms/cm and the 'volts/cm' switch is on 0.2 V/cm. Determine (a) the periodic time, (b) the frequency, (c) the magnitude of the pulse voltage.

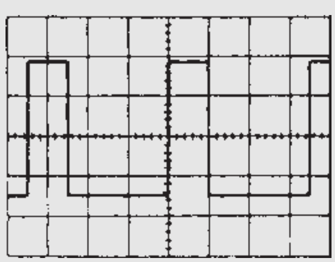

Figure 10.18

(a) The width of one complete cycle is 3.5 cm

Hence the periodic time, $T = 3.5\,\text{cm} \times 50\,\text{ms/cm}$
$= \mathbf{175\,ms}$

(b) Frequency, $f = \frac{1}{T} = \frac{1}{0.175} = \mathbf{5.71\,Hz}$

(c) The height of a pulse is 3.4 cm, hence the magnitude of the pulse voltage $= 3.4\,\text{cm} \times 0.2\,\text{V/cm} =$ **0.68 V**

Problem 9. A sinusoidal voltage trace displayed by an oscilloscope is shown in Figure 10.19. If the 'time/cm' switch is on 500 μs/cm and the 'volts/cm' switch is on 5 V/cm, find, for the waveform, (a) the frequency, (b) the peak-to-peak voltage, (c) the amplitude, (d) the r.m.s. value.

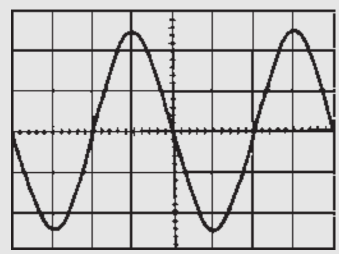

Figure 10.19

(a) The width of one complete cycle is 4 cm. Hence the periodic time, T is 4 cm × 500 μs/cm, i.e. 2 ms

Frequency, $f = \frac{1}{T} = \frac{1}{2 \times 10^{-3}} = \mathbf{500\,Hz}$

(b) The peak-to-peak height of the waveform is 5 cm. Hence the peak-to-peak voltage $= 5\,\text{cm} \times 5\,\text{V/cm}$
$= \mathbf{25\,V}$

(c) Amplitude $\frac{1}{2} \times 25\,V = \mathbf{12.5\,V}$

(d) The peak value of voltage is the amplitude, i.e. 12.5 V.

r.m.s. voltage $= \frac{\text{peak voltage}}{\sqrt{2}} = \frac{12.5}{\sqrt{2}} = \mathbf{8.84\,V}$

Problem 10. For the double-beam oscilloscope displays shown in Figure 10.20, determine (a) their frequency, (b) their r.m.s. values, (c) their phase difference. The 'time/cm' switch is on 100 μs/cm and the 'volts/cm' switch on 2 V/cm.

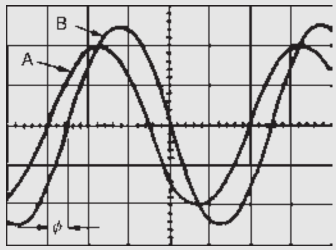

Figure 10.20

(a) The width of each complete cycle is 5 cm for both waveforms. Hence the periodic time, T, of each waveform is 5 cm × 100 μs/cm, i.e. 0.5 ms.

Frequency of each waveform, $f = \frac{1}{T} = \frac{1}{0.5 \times 10^{-3}}$

$= \mathbf{2\,kHz}$

(b) The peak value of waveform A is
$2\,\text{cm} \times 2\,\text{V/cm} = \mathbf{4\,V}$,

hence the r.m.s. value of waveform A

$$= \frac{4}{\sqrt{2}} = \mathbf{2.83\,V}$$

The peak value of waveform B is
$2.5\,\text{cm} \times 2\,\text{V/cm} = 5\,\text{V}$,

hence the r.m.s. value of waveform B

$$= \frac{5}{\sqrt{2}} = \mathbf{3.54\,V}$$

(c) Since 5 cm represents 1 cycle, then 5 cm represents 360°,

i.e. 1 cm represents $\frac{360}{5} = 72°$

The phase angle $\phi = 0.5\,\text{cm} = 0.5\,\text{cm} \times 72°/\text{cm}$
$= 36°$

Hence waveform A leads waveform B by 36°

Now try the following Practice Exercise

Practice Exercise 34 The oscilloscope (Answers on page 745)

1. For the square voltage waveform displayed on an oscilloscope shown in Figure 10.21, find (a) its frequency, (b) its peak-to-peak voltage.

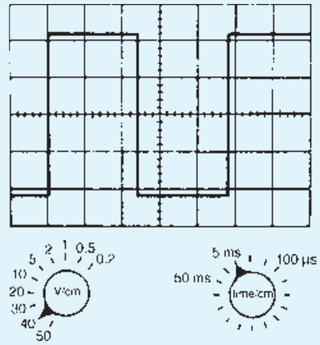

Figure 10.21

2. For the pulse waveform shown in Figure 10.22, find (a) its frequency, (b) the magnitude of the pulse voltage.

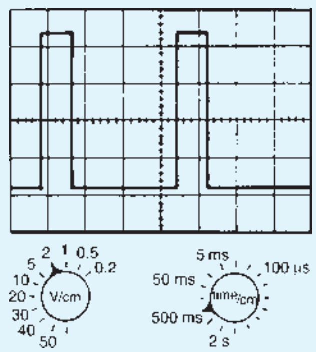

Figure 10.22

3. For the sinusoidal waveform shown in Figure 10.23, determine (a) its frequency, (b) the peak-to-peak voltage, (c) the r.m.s. voltage.

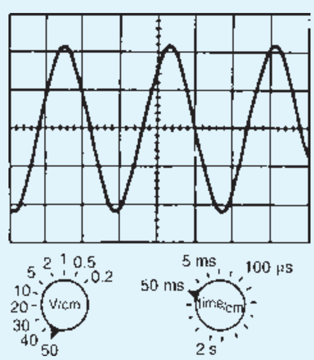

Figure 10.23

10.13 Virtual test and measuring instruments

Computer-based instruments are rapidly replacing items of conventional test equipment in many of today's test and measurement applications. Probably the most commonly available virtual test instrument is the digital storage oscilloscope (DSO). Because of the processing power available from the PC coupled with the mass storage capability, a computer-based virtual DSO is able to provide a variety of additional functions, such as spectrum analysis and digital display of both frequency and voltage. In addition, the ability to save waveforms and captured measurement data for future analysis or for comparison purposes can be extremely valuable, particularly where evidence of conformance with standards or specifications is required.

Unlike a conventional oscilloscope (which is primarily intended for waveform display), a computer-based virtual oscilloscope effectively combines several test instruments in one single package. The functions and available measurements from such an instrument usually includes:

- real-time or stored waveform display
- precise time and voltage measurement (using adjustable cursors)
- digital display of voltage
- digital display of frequency and/or periodic time
- accurate measurement of phase angle
- frequency spectrum display and analysis
- data logging (stored waveform data can be exported in formats that are compatible with conventional spreadsheet packages, e.g. as .xls files)
- ability to save/print waveforms and other information in graphical format (e.g. as .jpg or .bmp files).

Virtual instruments can take various forms, including:

- internal hardware in the form of a conventional PCI expansion card
- external hardware unit which is connected to the PC by means of either a conventional 25-pin parallel port connector or by means of a serial USB connector.

The software (and any necessary drivers) is invariably supplied on CD-ROM or can be downloaded from the manufacturer's website. Some manufacturers also supply software drivers together with sufficient accompanying documentation in order to allow users to control virtual test instruments from their own software developed using popular programming languages such as VisualBASIC or C++.

10.14 Virtual digital storage oscilloscopes

Several types of virtual DSO are currently available. These can be conveniently arranged into three different categories according to their application:

- low-cost DSO
- high-speed DSO
- high-resolution DSO.

Unfortunately, there is often some confusion between the last two categories. A high-speed DSO is designed for examining waveforms that are rapidly changing. Such an instrument does not necessarily provide high-resolution measurement. Similarly, a high-resolution DSO is useful for displaying waveforms with a high degree of precision, but it may not be suitable for examining fast waveforms. The difference between these two types of DSO should become a little clearer later on.

Low-cost DSO are primarily designed for low-frequency signals (typically signals up to around 20 kHz) and are usually able to sample their signals at rates of between 10 K and 100 K samples per second. Resolution is usually limited to either 8-bits or 12-bits (corresponding to 256 and 4096 discrete voltage levels, respectively).

High-speed DSOs are rapidly replacing CRT-based oscilloscopes. They are invariably dual-channel instruments and provide all the features associated with a conventional 'scope', including trigger selection, time-base and voltage ranges, and an ability to operate in X–Y mode.

Additional features available with a computer-based instrument include the ability to capture transient signals (as with a conventional digital storage 'scope') and save waveforms for future analysis. The ability to analyse a signal in terms of its frequency spectrum is yet another feature that is only possible with a DSO (see later).

Upper frequency limit

The upper signal frequency limit of a DSO is determined primarily by the rate at which it can sample an incoming signal. Typical sampling rates for different types of virtual instrument are:

Type of DSO	Typical sampling rate
Low-cost DSO	20 K to 100 K per second
High-speed DSO	100 M to 1000 M per second
High-resolution DSO	20 M to 100 M per second

In order to display waveforms with reasonable accuracy it is normally suggested that the sampling rate should be *at least* twice and *preferably more* than five times the highest signal frequency. Thus, in order to display a 10 MHz signal with any degree of accuracy a sampling rate of 50 M samples per second will be required.

The 'five times rule' merits a little explanation. When sampling signals in a digital-to-analogue converter we usually apply the **Nyquist*** criterion that the sampling frequency must be at least twice the highest analogue signal frequency. Unfortunately, this no longer applies in the case of a DSO where we need to sample at an even faster rate if we are to accurately display the signal. In practise we would need a minimum of about five points within a single cycle of a sampled waveform in order to reproduce it with approximate fidelity. Hence the sampling rate should be at least five times that of the highest signal frequency in order to display a waveform reasonably faithfully.

A special case exists with dual channel DSOs. Here the sampling rate may be shared between the two channels. Thus an effective sampling rate of 20 M samples per second might equate to 10 M samples per second for *each* of the two channels. In such a case the upper frequency limit would not be 4 MHz but only a mere 2 MHz.

The approximate bandwidth required to display different types of signals with reasonable precision is given in the table below:

Signal	Bandwidth required (approx.)
Low-frequency and power	d.c. to 10 kHz
Audio frequency (general)	d.c. to 20 kHz
Audio frequency (high-quality)	d.c. to 50 kHz
Square and pulse waveforms (up to 5 kHz)	d.c. to 100 kHz
Fast pulses with small rise-times	d.c. to 1 MHz
Video	d.c. to 10 MHz
Radio (LF, MF and HF)	d.c. to 50 MHz

*Who was **Nyquist**? Go to www.routledge.com/cw/bird

The general rule is that, for sinusoidal signals, the bandwidth should ideally be at least double that of the highest signal frequency whilst for square wave and pulse signals, the bandwidth should be at least ten times that of the highest signal frequency.

It is worth noting that most manufacturers define the bandwidth of an instrument as the frequency at which a sine wave input signal will fall to 0.707 of its true amplitude (i.e. the −3 dB point). To put this into context, at the cut-off frequency the displayed trace will be in error by a whopping 29%!

Resolution

The relationship between resolution and signal accuracy (not bandwidth) is simply that the more bits used in the conversion process the more discrete voltage levels can be resolved by the DSO. The relationship is as follows:

$$x = 2^n$$

where x is the number of discrete voltage levels and n is the number of bits. Thus, each time we use an additional bit in the conversion process we double the resolution of the DSO, as shown in the table below:

Number of bits, n	Number of discrete voltage levels, x
8-bit	256
10-bit	1024
12-bit	4096
16-bit	65 536

Buffer memory capacity

A DSO stores its captured waveform samples in a buffer memory. Hence, for a given sampling rate, the size of this memory buffer will determine for how long the DSO can capture a signal before its buffer memory becomes full.

The relationship between sampling rate and buffer memory capacity is important. A DSO with a high sampling rate but small memory will only be able to use its full sampling rate on the top few time base ranges.

To put this into context, it's worth considering a simple example. Assume that we need to display 10 000 cycles of a 10 MHz square wave. This signal will occur in a time frame of 1 ms. If applying the 'five times rule' we would need a bandwidth of at least 50 MHz to display this signal accurately.

To reconstruct the square wave we would need a minimum of about five samples per cycle so a minimum sampling rate would be $5 \times 10\,\text{MHz} = 50\,\text{M}$ samples per second. To capture data at the rate of 50 M samples per second for a time interval of 1 ms requires a memory that can store 50 000 samples. If each sample uses 16-bits we would require 100 kbyte of extremely fast memory.

Accuracy

The measurement resolution or measurement accuracy of a DSO (in terms of the smallest voltage change that can be measured) depends on the actual range that is selected. So, for example, on the 1 V range an 8-bit DSO is able to detect a voltage change of one two hundred and fifty sixth of a volt or (1/256) V or about 4 mV. For most measurement applications this will prove to be perfectly adequate as it amounts to an accuracy of about 0.4% of full-scale.

Figure 10.24 depicts a PicoScope software display showing multiple windows providing conventional oscilloscope waveform display, spectrum analyser display, frequency display and voltmeter display.

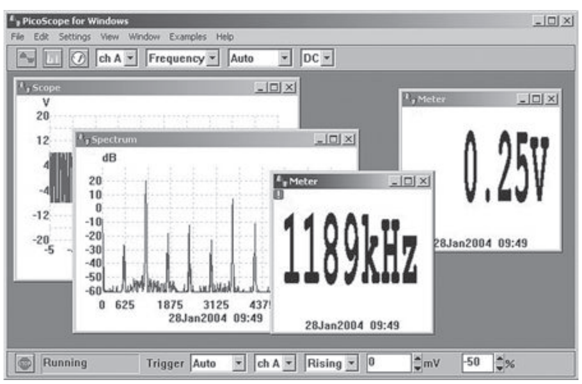

Figure 10.24

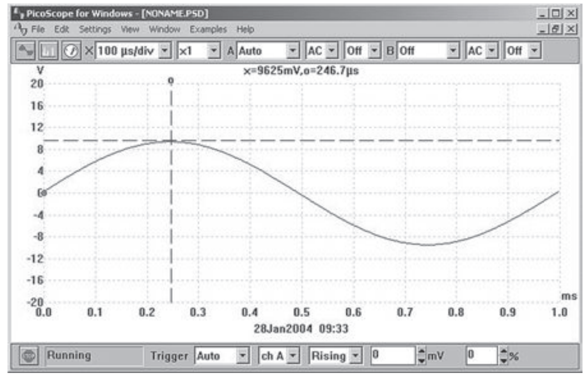

Figure 10.25

Adjustable cursors make it possible to carry out extremely accurate measurements. In Figure 10.25 the peak value of the (nominal 10 V peak) waveform is measured at precisely 9625 mV (9.625 V). The time to reach the peak value (from 0 V) is measured as 246.7 µs (0.2467 ms).

The addition of a second time cursor makes it possible to measure the time accurately between two events. In Figure 10.26, event 'o' occurs 131 ns before the trigger point whilst event 'x' occurs 397 ns after the trigger point. The elapsed time between these two events is 528 ns. The two cursors can be adjusted by means of the mouse (or other pointing device) or, more accurately, using the PC's cursor keys.

Autoranging

Autoranging is another very useful feature that is often provided with a virtual DSO. If you regularly use a conventional 'scope' for a variety of measurements you will know only too well how many times you need

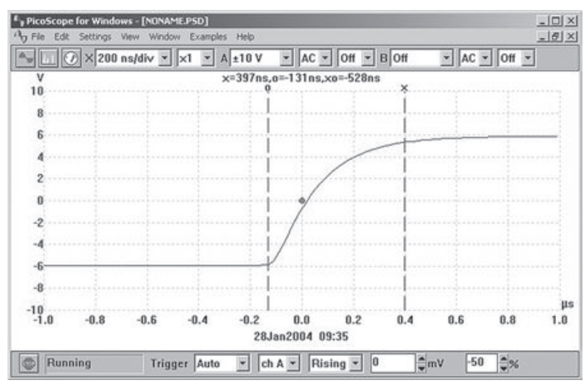

Figure 10.26

to make adjustments to the vertical sensitivity of the instrument.

High-resolution DSO

High-resolution DSOs are used for precision applications where it is necessary to faithfully reproduce a waveform and also to be able to perform an accurate analysis of noise floor and harmonic content. Typical applications include small-signal work and high-quality audio.

Unlike the low-cost DSO, which typically has 8-bit resolution and poor d.c. accuracy, these units are usually accurate to better than 1% and have either 12-bit or 16-bit resolution. This makes them ideal for audio, noise and vibration measurements.

The increased resolution also allows the instrument to be used as a spectrum analyser with very wide dynamic range (up to 100 dB). This feature is ideal for performing noise and distortion measurements on low-level analogue circuits.

Bandwidth alone is not enough to ensure that a DSO can accurately capture a high-frequency signal. The goal of manufacturers is to achieve a flat frequency response. This response is sometimes referred to as a Maximally Flat Envelope Delay (MFED). A frequency response of this type delivers excellent pulse fidelity with minimum overshoot, undershoot and ringing.

It is important to remember that if the input signal is not a pure sine wave it will contain a number of higher-frequency harmonics. For example, a square wave will contain odd harmonics that have levels that become progressively reduced as their frequency increases. Thus, to display a 1 MHz square wave accurately you need to take into account the fact that there will be signal components present at 3 MHz, 5 MHz, 7 MHz, 9 MHz, 11 MHz and so on.

Spectrum analysis

The technique of Fast Fourier Transformation (FFT) calculated using software algorithms using data captured by a virtual DSO has made it possible to produce frequency spectrum displays. Such displays can be used to investigate the harmonic content of waveforms as well as the relationship between several signals within a composite waveform.

Figure 10.27 shows the frequency spectrum of the 1 kHz sine wave signal from a low-distortion signal generator. Here the virtual DSO has been set to capture samples at a rate of 4096 per second within a frequency range of d.c. to 12.2 kHz. The display clearly shows the second harmonic (at a level of −50 dB or −70 dB relative to the fundamental), plus further harmonics at 3 kHz, 5 kHz and 7 kHz (all of which are greater than 75 dB down on the fundamental).

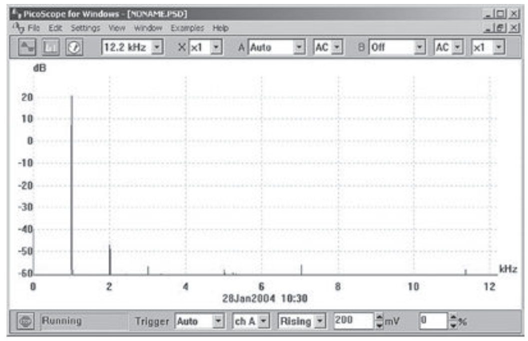

Figure 10.27

Problem 11. Figure 10.28 shows the frequency spectrum of a signal at 1184 kHz displayed by a high-speed virtual DSO. Determine (a) the harmonic relationship between the signals marked 'o' and 'x', (b) the difference in amplitude (expressed in dB) between the signals marked 'o' and 'x' and (c) the amplitude of the second harmonic relative to the fundamental signal 'o'

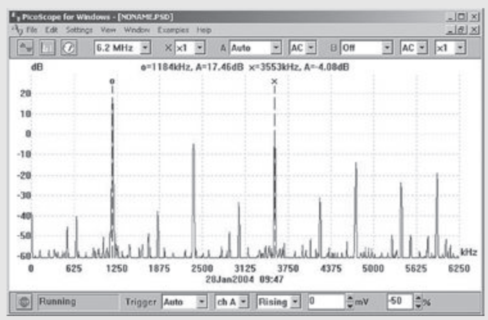

Figure 10.28

(a) The signal x is at a frequency of 3553 kHz. This is three times the frequency of the signal at 'o' which is at 1184 kHz. Thus, **x is the third harmonic of the signal 'o'**

(b) The signal at 'o' has an amplitude of +17.46 dB whilst the signal at 'x' has an amplitude of −4.08 dB. Thus, **the difference in level** $= (+17.46) - (-4.08) =$ **21.54 dB**

(c) **The amplitude of the second harmonic** (shown at approximately 2270 kHz) $=$ **−5 dB**

10.15 Waveform harmonics

(i) Let an instantaneous voltage v be represented by $v = V_m \sin 2\pi ft$ volts. This is a waveform which varies sinusoidally with time t, has a frequency f, and a maximum value V_m. Alternating voltages are usually assumed to have wave shapes which are sinusoidal, where only one frequency is present. If the waveform is not sinusoidal it is called a **complex wave**, and, whatever its shape, it may be split up mathematically into components called the **fundamental** and a number of **harmonics**. This process is called harmonic analysis. The fundamental (or first harmonic) is sinusoidal and has the supply frequency, f; the other harmonics are also sine waves having frequencies which are integer multiples of f. Thus, if the supply frequency is 50 Hz, then the third harmonic frequency is 150 Hz, the fifth 250 Hz, and so on.

(ii) A complex waveform comprising the sum of the fundamental and a third harmonic of about half the amplitude of the fundamental is shown in Figure 10.29(a), both waveforms being initially in phase with each other. If further odd harmonic waveforms of the appropriate amplitudes are added, a good approximation to a square wave results. In Figure 10.29(b), the third harmonic is shown having an initial phase displacement from the fundamental. The positive and negative half cycles of each of the complex waveforms shown in Figures 10.29(a) and (b) are identical in shape, and this is a feature of waveforms containing the fundamental and only odd harmonics.

(iii) A complex waveform comprising the sum of the fundamental and a second harmonic of about half the amplitude of the fundamental is shown in Figure 10.29(c), each waveform being initially in phase with each other. If further even harmonics of appropriate amplitudes are added a good approximation to a triangular wave results. In Figure 10.29(c) the negative cycle appears as a mirror image of the positive cycle about point A. In Figure 10.29(d) the second harmonic is shown with an initial phase displacement from the fundamental and the positive and negative half cycles are dissimilar.

(iv) A complex waveform comprising the sum of the fundamental, a second harmonic and a third harmonic is shown in Figure 10.29(e), each waveform being initially 'in-phase'. The negative half cycle appears as a mirror image of the positive cycle about point B. In Figure 10.29(f), a complex waveform comprising the sum of the fundamental, a second harmonic and a third harmonic are shown with initial phase displacement. The positive and negative half cycles are seen to be dissimilar.

The features mentioned relative to Figures 10.29(a) to (f) make it possible to recognize the harmonics present in a complex waveform displayed on an oscilloscope.

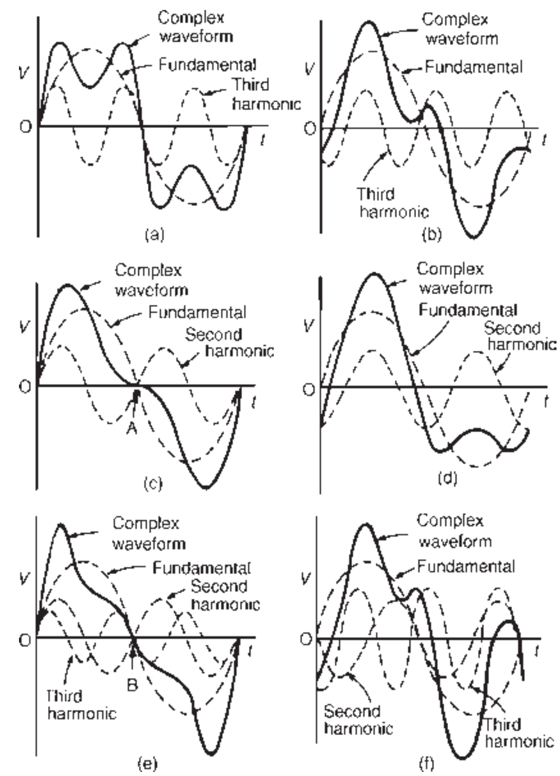

Figure 10.29

More on complex waveforms may be found in Chapter 36, page 505.

10.16 Logarithmic ratios

In electronic systems, the ratio of two similar quantities measured at different points in the system are often expressed in logarithmic units. By definition, if the ratio of two powers P_1 and P_2 is to be expressed in **decibel (dB) units**, then the number of decibels, X, is given by:

$$X = 10 \lg \left(\frac{P_2}{P_1}\right) \text{dB} \qquad (1)$$

A decibel is one-tenth of a bel, the bel being a unit named in honour of **Alexander Graham Bell**.*

Thus, when the power ratio,

$\frac{P_2}{P_1} = 1$ then the decibel power ratio

$= 10 \lg 1 = 0$

when the power ratio,

$\frac{P_2}{P_1} = 100$ then the decibel power ratio

$= 10 \lg 100 = +20$

(i.e. a power gain),

and when the power ratio,

$\frac{P_2}{P_1} = \frac{1}{100}$ then the decibel power ratio

$= 10 \lg \frac{1}{100} = -20$

(i.e. a power loss or attenuation).

Logarithmic units may also be used for voltage and current ratios.

Power, P, is given by $P = I^2R$ or $P = V^2/R$

Substituting in equation (1) gives:

$$X = 10 \lg \left(\frac{I_2^2 R_2}{I_1^2 R_1}\right) \text{dB or } X = 10 \lg \left(\frac{V_2^2/R_2}{V_1^2/R_1}\right) \text{dB}$$

If $R_1 = R_2$ then $X = 10 \lg \left(\frac{I_2^2}{I_1^2}\right)$ dB or $X = 10 \lg \left(\frac{V_2^2}{V_1^2}\right)$ dB

i.e. $\mathbf{X = 20 \lg \left(\frac{I_2}{I_1}\right) dB}$ or $\mathbf{X = 20 \lg \left(\frac{V_2}{V_1}\right) dB}$

(from the laws of logarithms).

From equation (1), X decibels is a logarithmic ratio of two similar quantities and is not an absolute unit of measurement. It is therefore necessary to state a **reference level** to measure a number of decibels above or below that reference. The most widely used reference level for power is 1 mW, and when power levels are expressed in decibels, above or below the 1 mW reference level, the unit given to the new power level is dBm.

*Who was **Bell**? Go to www.routledge.com/cw/bird

A voltmeter can be re-scaled to indicate the power level directly in decibels. The scale is generally calibrated by taking a reference level of 0 dB when a power of 1 mW is dissipated in a 600 Ω resistor (this being the natural impedance of a simple transmission line). The reference voltage V is then obtained from

$P = \frac{V^2}{R}$, i.e. $1 \times 10^{-3} = \frac{V^2}{600}$ from which,

$V = 0.775$ volts

In general, the number of dBm, $X = 20 \lg \left(\frac{V}{0.775}\right)$

Thus $V = 0.20$ V corresponds to $20 \lg \left(\frac{0.20}{0.775}\right)$

$= -11.77$ dBm and

$V = 0.90$ V corresponds to $20 \lg \left(\frac{0.90}{0.775}\right)$

$= +1.3$ dBm, and so on.

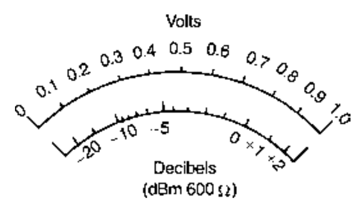

Figure 10.30

A typical **decibelmeter**, or **dB meter**, scale is shown in Figure 10.30. Errors are introduced with dB meters when the circuit impedance is not 600 Ω.

Problem 12. The ratio of two powers is (a) 3, (b) 20, (c) 400, (d) $\frac{1}{20}$. Determine the decibel power ratio in each case.

From above, the power ratio in decibels, X, is given by: $X = 10 \lg \left(\frac{P_2}{P_1}\right)$

(a) When $\frac{P_2}{P_1} = 3$, $X = 10 \lg(3) = 10(0.477)$

$= \mathbf{4.77\,dB}$

(b) When $\frac{P_2}{P_1} = 20$, $X = 10 \lg(20) = 10(1.30)$

$= \mathbf{13.0\,dB}$

(c) When $\frac{P_2}{P_1} = 400$, $X = 10 \lg(400) = 10(2.60)$

$= \mathbf{26.0\,dB}$

(d) When $\frac{P_2}{P_1} = \frac{1}{20} = 0.05$, $X = 10\,\lg(0.05)$
$= 10(-1.30) = \mathbf{-13.0\,dB}$

(a), (b) and (c) represent power gains and (d) represents a power loss or attenuation.

Problem 13. The current input to a system is 5 mA and the current output is 20 mA. Find the decibel current ratio, assuming the input and load resistances of the system are equal.

From above, the decibel current ratio is

$$20\lg\left(\frac{I_2}{I_1}\right) = 20\lg\left(\frac{20}{5}\right) = 20\lg 4 = 20(0.60) = \mathbf{12\,dB\ gain}$$

Problem 14. 6% of the power supplied to a cable appears at the output terminals. Determine the power loss in decibels.

If P_1 = input power and P_2 = output power then $\frac{P_2}{P_1} = \frac{6}{100} = 0.06$

$$\text{Decibel power ratio} = 10\lg\left(\frac{P_2}{P_1}\right) = 10\lg(0.06) = 10(-1.222) = -12.22\,\text{dB}$$

Hence the decibel power loss, or attenuation, is 12.22 dB

Problem 15. An amplifier has a gain of 14 dB. Its input power is 8 mW. Find its output power.

$$\text{Decibel power ratio} = 10\,\lg\left(\frac{P_2}{P_1}\right)$$

where P_1 = input power = 8 mW,
and P_2 = output power

$$\text{Hence } 14 = 10\lg\left(\frac{P_2}{P_1}\right)$$

$$1.4 = \lg\left(\frac{P_2}{P_1}\right)$$

and $10^{1.4} = \frac{P_2}{P_1}$ from the definition of a logarithm

i.e. $25.12 = \frac{P_2}{P_1}$

Output power, $P_2 = 25.12$, $P_1 = (25.12)(8) = \mathbf{201\,mW}$ or **0.201 W**

Problem 16. The output voltage from an amplifier is 4 V. If the voltage gain is 27 dB, calculate the value of the input voltage assuming that the amplifier input resistance and load resistance are equal.

$$\text{Voltage gain in decibels} = 27 = 20\,\lg\left(\frac{V_2}{V_1}\right) = 20\,\lg\left(\frac{4}{V_1}\right)$$

$$\text{Hence } \frac{27}{20} = \lg\left(\frac{4}{V_1}\right)$$

$$1.35 = \lg\left(\frac{4}{V_1}\right)$$

$$10^{1.35} = \frac{4}{V_1}, \text{ from which}$$

$$V_1 = \frac{4}{10^{1.35}} = \frac{4}{22.39} = 0.179\,\text{V}$$

Hence the input voltage V_1 is 0.179 V.

Now try the following Practice Exercise

Practice Exercise 35 Logarithmic ratios (Answers on page 745)

1. The ratio of two powers is (a) 3, (b) 10, (c) 20, (d) 10 000. Determine the decibel power ratio for each.
2. The ratio of two powers is (a) $\frac{1}{10}$, (b) $\frac{1}{3}$, (c) $\frac{1}{40}$, (d) $\frac{1}{100}$ Determine the decibel power ratio for each.
3. The input and output currents of a system are 2 mA and 10 mA, respectively. Determine the decibel current ratio of output to input current assuming input and output resistances of the system are equal.
4. 5% of the power supplied to a cable appears at the output terminals. Determine the power loss in decibels.
5. An amplifier has a gain of 24 dB. Its input power is 10 mW. Find its output power.
6. The output voltage from an amplifier is 7 mV. If the voltage gain is 25 dB, calculate the value

of the input voltage assuming that the amplifier input resistance and load resistance are equal.

7. The scale of a voltmeter has a decibel scale added to it, which is calibrated by taking a reference level of 0 dB when a power of 1 mW is dissipated in a 600 Ω resistor. Determine the voltage at (a) 0 dB, (b) 1.5 dB, and (c) −15 dB (d) What decibel reading corresponds to 0.5 V?

10.17 Null method of measurement

A **null method of measurement** is a simple, accurate and widely used method which depends on an instrument reading being adjusted to read zero current only. The method assumes:

(i) if there is any deflection at all, then some current is flowing;

(ii) if there is no deflection, then no current flows (i.e. a null condition).

Hence it is unnecessary for a meter sensing current flow to be calibrated when used in this way. A sensitive milliammeter or microammeter with centre-zero position setting is called a **galvanometer**. Examples where the method is used are in the Wheatstone bridge (see Section 10.18), in the d.c. potentiometer (see Section 10.19) and with a.c. bridges (see Section 10.20).

10.18 Wheatstone bridge

Figure 10.31 shows a **Wheatstone*** bridge circuit which compares an unknown resistance R_x with others of known values, i.e. R_1 and R_2, which have fixed values, and R_3, which is variable. R_3 is varied until zero deflection is obtained on the galvanometer G. No current then flows through the meter, $V_A = V_B$, and the bridge is said to be 'balanced'.

At balance, $R_1R_x = R_2R_3$, i.e. $\boldsymbol{R_x = \frac{R_2R_3}{R_1}}$ **ohms**

*Who was **Wheatstone**? Go to www.routledge.com/cw/bird

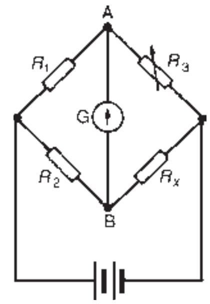

Figure 10.31

Problem 17. In a Wheatstone bridge *ABCD*, a galvanometer is connected between A and C, and a battery between B and D. A resistor of unknown value is connected between A and B. When the bridge is balanced, the resistance between B and C is 100 Ω, that between C and D is 10 Ω and that between D and A is 400 Ω. Calculate the value of the unknown resistance.

The Wheatstone bridge is shown in Figure 10.32 where R_x is the unknown resistance. At balance, equating the products of opposite ratio arms gives:

$(R_x)(10) = (100)(400)$

and $R_x = \frac{(100)(400)}{10} = 4000\,\Omega$

Hence the unknown resistance, $R_x = 4\,k\Omega$

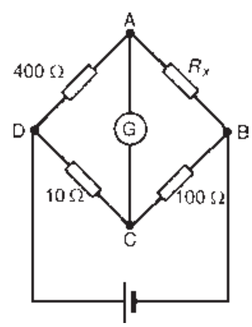

Figure 10.32

10.19 D.c. potentiometer

The **d.c. potentiometer** is a null-balance instrument used for determining values of e.m.f.s and p.d.s. by comparison with a known e.m.f. or p.d. In Figure 10.33(a), using a standard cell of known e.m.f. E_1, the slider S is moved along the slide wire until balance is obtained (i.e. the galvanometer deflection is zero), shown as length l_1

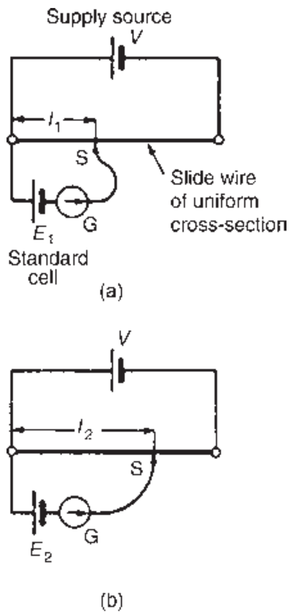

Figure 10.33

The standard cell is now replaced by a cell of unknown e.m.f., E_2 (see Figure 10.33(b)), and again balance is obtained (shown as l_2).

Since $E_1 \alpha l_1$ and $E_2 \alpha l_2$ then $\frac{E_1}{E_2} = \frac{l_1}{l_2}$

and $$\boldsymbol{E_2 = E_1\left(\frac{l_2}{l_1}\right)} \textbf{ volts}$$

A potentiometer may be arranged as a resistive two-element potential divider in which the division ratio is adjustable to give a simple variable d.c. supply. Such devices may be constructed in the form of a resistive element carrying a sliding contact which is adjusted by a rotary or linear movement of the control knob.

Problem 18. In a d.c. potentiometer, balance is obtained at a length of 400 mm when using a standard cell of 1.0186 volts. Determine the e.m.f. of a dry cell if balance is obtained with a length of 650 mm.

$E_1 = 1.0186$ V, $l_1 = 400$ mm, $l_2 = 650$ mm

With reference to Figure 10.33, $\frac{E_1}{E_2} = \frac{l_1}{l_2}$

from which, $E_2 = E_1\left(\frac{l_2}{l_1}\right) = (1.0186)\left(\frac{650}{400}\right)$

$= \mathbf{1.655}$ **volts**

Now try the following Practice Exercise

Practice Exercise 36 Wheatstone bridge and d.c. potentiometer (Answers on page 746)

1. In a Wheatstone bridge *PQRS*, a galvanometer is connected between Q and S and a voltage source between P and R. An unknown resistor R_x is connected between P and Q. When the bridge is balanced, the resistance between Q and R is 200 Ω, that between R and S is 10 Ω and that between S and P is 150 Ω. Calculate the value of R_x

2. Balance is obtained in a d.c. potentiometer at a length of 31.2 cm when using a standard cell of 1.0186 volts. Calculate the e.m.f. of a dry cell if balance is obtained with a length of 46.7 cm.

10.20 A.c. bridges

A Wheatstone bridge type circuit, shown in Figure 10.34, may be used in a.c. circuits to determine unknown values of inductance and capacitance, as well as resistance.

When the potential differences across Z_3 and Z_x (or across Z_1 and Z_2) are equal in magnitude and phase, then the current flowing through the galvanometer, G, is zero.

At balance, $Z_1 Z_x = Z_2 Z_3$, from which,

$$\boldsymbol{Z_x = \frac{Z_2 Z_3}{Z_1}\ \Omega}$$

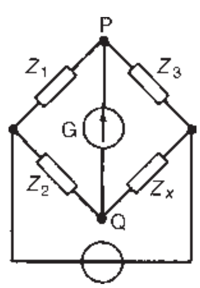

Figure 10.34

There are many forms of a.c. bridge, and these include: the Maxwell, Hay, Owen and Heaviside bridges for measuring inductance, and the De Sauty, Schering and Wien bridges for measuring capacitance. A **commercial or universal bridge** is one which can be used to measure resistance, inductance or capacitance.

A.c. bridges require a knowledge of complex numbers, as explained in Chapter 23, and such bridges are discussed in detail in Chapter 27.

10.21 Measurement errors

Errors are always introduced when using instruments to measure electrical quantities. The errors most likely to occur in measurements are those due to:

(i) the limitations of the instrument

(ii) the operator

(iii) the instrument disturbing the circuit

(i) Errors in the limitations of the instrument

The **calibration accuracy** of an instrument depends on the precision with which it is constructed. Every instrument has a margin of error which is expressed as a percentage of the instrument's full-scale deflection.

For example, industrial-grade instruments have an accuracy of ±2% of f.s.d. Thus if a voltmeter has an f.s.d. of 100 V and it indicates 40 V, say, then the actual voltage may be anywhere between 40 ± (2% of 100), or 40 ± 2, i.e. between 38 V and 42 V.

When an instrument is calibrated, it is compared against a standard instrument and a graph is drawn of 'error' against 'meter deflection'.

A typical graph is shown in Figure 10.35 where it is seen that the accuracy varies over the scale length. Thus a meter with a ±2% f.s.d. accuracy would tend to have an accuracy which is much better than ±2% f.s.d. over much of the range.

(ii) Errors by the operator

It is easy for an operator to misread an instrument. With linear scales the values of the sub-divisions are reasonably easy to determine; non-linear scale graduations are more difficult to estimate. Also, scales differ from instrument to instrument and some meters have more than one scale (as with multimeters) and mistakes in reading indications are easily made. When reading a meter scale it should be viewed from an angle perpendicular to the surface of the scale at the location of the pointer; a meter scale should not be viewed 'at an angle'. Errors by the operator are largely eliminated using digital instruments.

(iii) Errors due to the instrument disturbing the circuit

Any instrument connected into a circuit will affect that circuit to some extent. Meters require some power to operate, but provided this power is small compared with the power in the measured circuit, then little error will result. Incorrect positioning of instruments in a circuit can be a source of errors. For example, let a resistance be measured by the voltmeter-ammeter method as shown in Figure 10.36. Assuming 'perfect' instruments, the resistance should be given by the voltmeter reading divided by the ammeter reading (i.e. $R = V/I$).

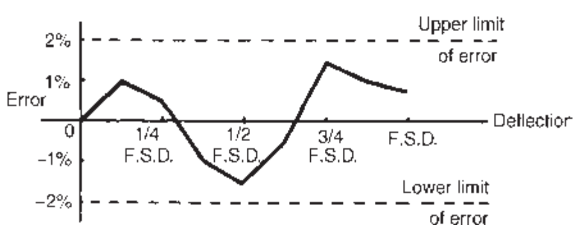

Figure 10.35

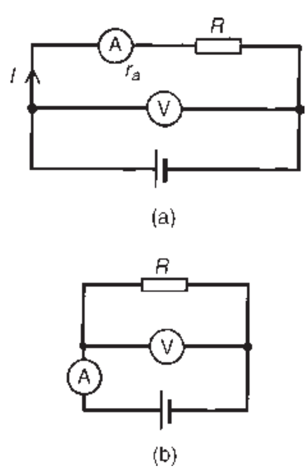

Figure 10.36

Part 1

However, in Figure 10.36(a), $V/I = R + r_a$ and in Figure 10.36(b) the current through the ammeter is that through the resistor plus that through the voltmeter. Hence the voltmeter reading divided by the ammeter reading will not give the true value of the resistance R for either method of connection.

Problem 19. The current flowing through a resistor of $5\,k\Omega \pm 0.4\%$ is measured as 2.5 mA with an accuracy of measurement of ±0.5%. Determine the nominal value of the voltage across the resistor and its accuracy.

Voltage, $V = IR = (2.5 \times 10^{-3})(5 \times 10^3) = 12.5\,V$.

The maximum possible error is 0.4% + 0.5% = 0.9%

Hence the voltage, $V = 12.5\,V \pm 0.9\%$ of 12.5 V $= 0.9/100 \times 12.5 = 0.1125\,V = 0.11\,V$ correct to 2 significant figures. Hence the voltage V may also be expressed as **12.5 ± 0.11 volts** (i.e. a voltage lying between 12.39 V and 12.61 V).

Problem 20. The current I flowing in a resistor R is measured by a 0–10 A ammeter which gives an indication of 6.25 A. The voltage V across the resistor is measured by a 0–50 V voltmeter, which gives an indication of 36.5 V. Determine the resistance of the resistor, and its accuracy of measurement if both instruments have a limit of error of 2% of f.s.d. Neglect any loading effects of the instruments.

Resistance, $R = \frac{V}{I} = \frac{36.5}{6.25} = 5.84\,\Omega$

Voltage error is ±2% of 50 V = ±1.0 V and expressed as a percentage of the voltmeter reading gives $\frac{\pm 1}{36.5} \times 100\% = \pm 2.74\%$

Current error is ±2% of 10 A = ±0.2 A and expressed as a percentage of the ammeter reading gives $\frac{\pm 0.2}{6.25} \times 100\% = \pm 3.2\%$

Maximum relative error = sum of errors = 2.74% + 3.2% = ±5.94%, and 5.94% of $5.84\,\Omega = 0.347\,\Omega$

Hence the resistance of the resistor may be expressed as: **5.84 Ω ± 5.94%**, or **5.84 ± 0.35 Ω** (rounding off).

Problem 21. The arms of a Wheatstone bridge *ABCD* have the following resistances: *AB*: $R_1 = 1000\,\Omega \pm 1.0\%$; *BC*: $R_2 = 100\,\Omega \pm 0.5\%$; *CD*: unknown resistance R_x; *DA*: $R_3 = 432.5\,\Omega \pm 0.2\%$. Determine the value of the unknown resistance and its accuracy of measurement.

The Wheatstone bridge network is shown in Figure 10.37 and at balance:

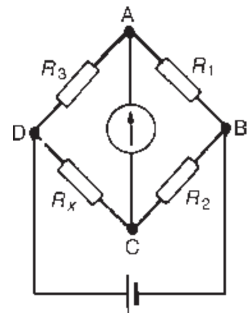

Figure 10.37

$$R_1 R_x = R_2 R_3, \text{ i.e. } R_x = \frac{R_2 R_3}{R_1} = \frac{(100)(432.5)}{1000} = 43.25\,\Omega$$

The maximum relative error of R_x is given by the sum of the three individual errors, i.e.
1.0% + 0.5% + 0.2% = 1.7%

Hence R_x = 43.25 Ω ± 1.7%

1.7% of 43.25 Ω = 0.74 Ω (rounding off).

Thus R_x may also be expressed as **R_x = 43.25 ± 0.74 Ω**

Now try the following Practice Exercise

Practice Exercise 37 Measurement errors (Answers on page 746)

1. The p.d. across a resistor is measured as 37.5 V with an accuracy of ±0.5%. The value of the resistor is 6 kΩ ± 0.8%. Determine the current flowing in the resistor and its accuracy of measurement.

2. The voltage across a resistor is measured by a 75 V f.s.d. voltmeter which gives an indication of 52 V. The current flowing in the resistor is measured by a 20 A f.s.d. ammeter which gives an indication of 12.5 A. Determine the

resistance of the resistor and its accuracy if both instruments have an accuracy of ±2% of f.s.d.

3. A Wheatstone bridge *PQRS* has the following arm resistances: *PQ*, 1 kΩ ± 2%; *QR*, 100 Ω ± 0.5%; *RS*, unknown resistance; *SP*, 273.6 Ω ± 0.1%. Determine the value of the unknown resistance, and its accuracy of measurement.

For fully worked solutions to each of the problems in Practice Exercises 32 to 37 in this chapter, go to the website:
www.routledge.com/cw/bird