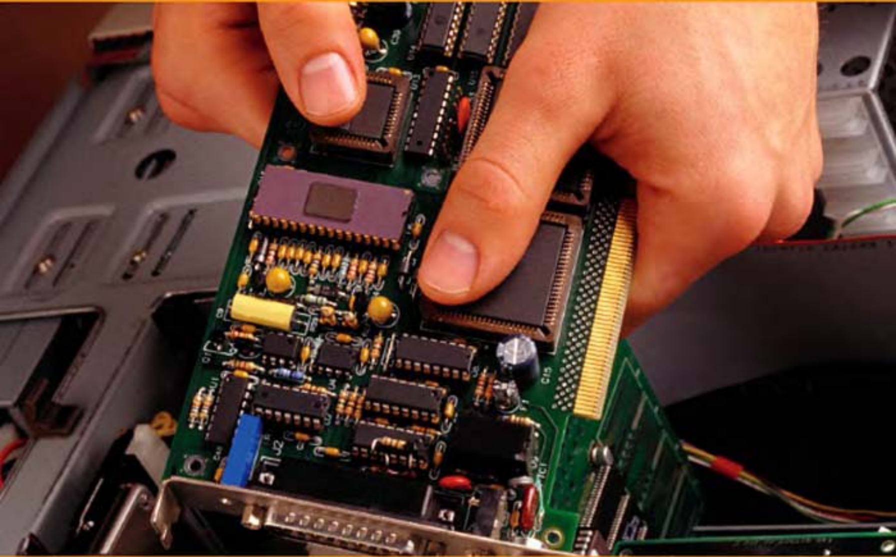
Second edition

Electronic and Electrical Servicing

Consumer and Commercial Electronics



Ian Sinclair & John Dunton

Newnes

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Second Edition

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and

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Contents

Preface to the second edition

This new edition of *Electronic and Electrical Servicing* reflects the rapid changes that are taking place within the electronics industry. In particular, we have to recognise that much of the equipment that requires servicing will be of older design and construction; by contrast, some modern equipment may require to be replaced under guarantee rather than be serviced. We also need to bear in mind that servicing some older equipment may be totally uneconomical, because it will cost more than replacement. With all this in mind, this new edition still provides information on older techniques, but also indicates how modern digital systems work and to what extent they can be serviced.

This volume is intended to provide a complete and rigorous course of instruction for Level 2 of the City & Guilds Progression Award in Electrical and Electronics Servicing – Consumer/Commercial Electronics (C&G 6958). For those students who wish to progress to Level 3, a further set of chapters covering all of the core units at this level is available as free downloads from the book's companion website or as a print-on-demand book with ISBN 978-0-7506-8732-4.

Companion website

Level 3 material available for free download from
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Ian Sinclair
John Dunton

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Unit 1

D.c. technology, components and circuits

Outcomes

1. Demonstrate an understanding of electrical units, primary cells and secondary cells and apply this knowledge in a practical situation
2. Demonstrate an understanding of cables, connectors, lamps and fuses and apply this knowledge in a practical situation
3. Demonstrate an understanding of resistors and potentiometers and apply this knowledge in a practical situation

Health and Safety. Note: The content of this topic has been placed later, as Chapter 25.

1

Direct current technology

Electric current consists of the flow of small particles called electrons in a circuit. Its rate of flow is measured in units called **amperes**, abbreviated either to ‘amps’ or ‘A’. One ampere is the amount of electric charge, in units called coulombs, that passes a given point in a circuit per second. The coulomb has a value of about 6.289×10^{18} electrons (10^{18} means a 1 followed by 18 zeros). The measurement of current is done, not by actually counting these millions of millions of millions of electric charges, but by measuring the amount of force that is exerted between a magnet and the wire carrying the current that is being measured. Current can flow in any material that allows electrons to move, but in such materials there is always some resistance to the flow of current (except for materials called *superconductors*). Resistance is measured in units called ohms, symbol Ω (the Green letter omega).

> Electric current can be direct current (d.c.) or alternating current (a.c.) or a mixture of both

Direct current is a steady flow of current, the type that occurs in a circuit fed by a battery. This type of current is used to operate most types of electronic circuit. Alternating current is not a steady flow; it is a current that rises to a peak in one direction, reverses and reaches a peak in the opposite direction and reverses again. This means that at times the current becomes zero and at other times it can be flowing in either direction.

Electronics makes use of a.c. with much smaller times for one cycle, and we usually prefer to refer to the number of cycles in a second, a quantity called **frequency**, rather than the time of one cycle. The unit of frequency is one complete cycle per second, called 1 hertz, abbreviation Hz. Looked at this way, the mains frequency is 50 Hz. The frequencies used for radio broadcasting are measured in millions of hertz, MHz. Computers typically work with thousands of millions of hertz, gigahertz, abbreviation GHz. In following chapters we’ll look at how a.c. behaves in circuits and the differences between a.c. and d.c.

In the same way as a pressure is needed to cause a flow of water through a pipe, so an electrical ‘pressure’ called **electromotive force** or **voltage** is needed to push a current through a resistance. Electromotive force (emf) is measured in units of volts, symbol V. A voltage is always present when a current is flowing through a resistance, and the three quantities of volts, amps and ohms (the unit of resistance) are related. Like current, voltage can be direct or alternating.

The ampere is a fairly large unit, and for most electronics purposes the smaller units milliamp (one-thousandth of an ampere) and microamp (one-millionth of an ampere) are more generally used. The abbreviations for these qualities are mA and µA, respectively. All electrical units can use the same set of smaller units **(submultiples)** and larger units (**multiples**), and some of the most common are listed in Table 1.1. The abbreviation list is of **SI prefixes**, the standard letters used to indicate the multiple or submultiple.

Table 1.1 Multiples and submultiples

Number	*Power*	*Written as*	*Abbreviation*
0.000 000 000 001	10^{-12}	pico-	p
0.000 000 001	10^{-9}	nano-	n
0.000 001	10^{-6}	micro-	µ
0.000 01	10^{-3}	milli-	m
1000	10^{3}	kilo-	k
1 000 000	10^{6}	mega-	M

Two simple examples will help to show how the system works. A current flow of 0.015 amperes can be more simply written as 15 mA (milliamps), which is 15×10^{-3} A. A resistance of 56 000 ohms, which is equal to 56×10^{3} ohms, is written as 56 k (**k** for kilohms). The ohm sign Ω is often left out.

Do not use K for kilo, because the K abbreviation is used for temperatures measured in kelvin. You may see the K in some circuit diagrams that were drawn before agreement was reached on how to represent kilohms.

There are two other important electrical units, of **energy** and of **power**. The energy unit is called the **joule**, abbreviation J, and it measures the amount of work that an electrical current can do, such as in an electric motor or a heater. The power unit measures the rate of doing work, which is the amount of work per second, and its unit is the **watt**, symbol W. Both the units can also make use of the multiples and submultiples in Table 1.1.

Circuits and current

An electric **circuit** is a closed path made from conducting material. When the path is not closed, it is an **open circuit**, and no current can flow. In a circuit that contains a battery and a lamp, for example, the lamp will light when the circuit is closed, and we take the direction of the conventional flow of current as from the positive (+) pole of the battery to the negative (−). This convention was agreed centuries ago, and we now know that the movement of electrons is in the opposite direction, from negative to positive. For most purposes, we stay with the old convention, but for some purposes in electronics we need to know the direction of the electron flow.

An electrical circuit such as the lamp and battery can be shown in two ways. One is to draw the battery and the bulb as they would appear to the eye. The other is to draw the shape of the circuit, representing items such as the battery and the lamp, the components of the circuit, as symbols, and the conductor as a line. We draw these **circuit diagrams** to show the path that the current takes, because this is more important than the appearance of the components. To avoid confusion, there are some rules (conventions) about drawing these circuits.

- A line represents a conductor
- Where lines cross, the conductors are NOT joined
- Where two lines meet in a T junction, with or without a dot, conductors are connected.

Figure 1.1 shows some symbols that are used for common components. Most of these use two connections only, but a few use three or more. These symbols are UK [British Standard (BS)] and European standards, but circuit diagrams from the USA and Japan may use the alternative symbols for resistors and capacitors.

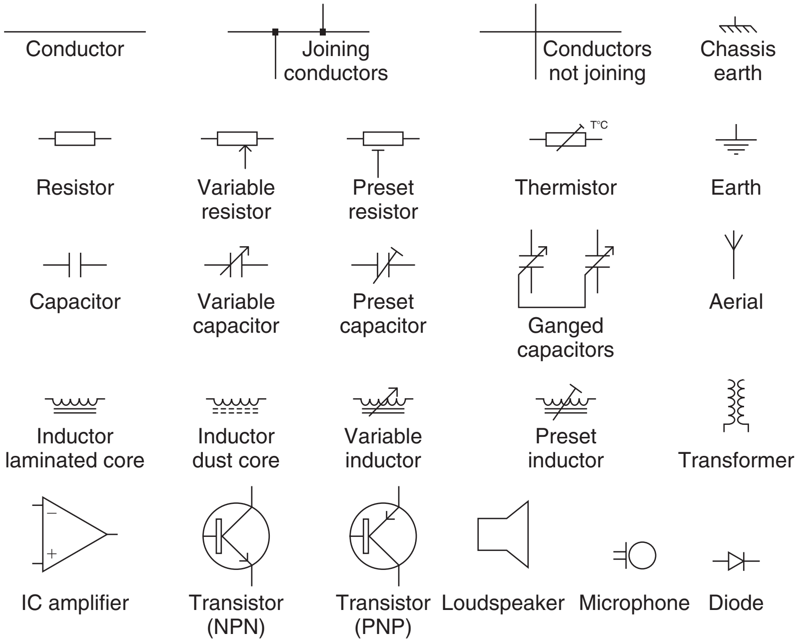


Figure 1.1 Some symbols used in UK circuit diagrams

Circuit diagrams are important because they are one of the main pieces of information about a circuit, whether it is a circuit for the wiring of a house or the circuit for a television receiver. For servicing purposes you must be able to read a circuit diagram and work out the path of currents.

Effects of current

Electric current causes three main effects, which have been known for several hundred years.

- **Heating effect**: when a current flows through a conductor, heat is generated so that the temperature of the conductor rises.
- **Magnetic effect**: when a current flows through a conductor it causes the conductor to become a magnet.
- **Chemical effect**: when a current flows through a chemical solution it can cause chemical separation (in addition to heating and magnetism).

All of these effects can be either useful or undesirable. We use the heating effect in electric fires and cookers, but we try to minimize the loss of energy from transmission cables by using high voltages with low current for transmission. The heating effect is the same whether the current is d.c. or a.c. The magnetic effect is used in electric motors, relays and solenoids (meaning magnets that can be switched on and off). Less desirable effects include the unwanted interference that comes from the magnetic fields created around wires. One notable wanted chemical effect is that of chemical energy being converted to electrical energy in a cell or battery. Some other chemical effects are, however, undesirable. A current that is passed through a solution of a salty material dissolved in water will cause a chemical change in the solution which can release corrosive substances. This is the effect that causes electrolytic corrosion, particularly on electrical equipment that is used in ships.

All of these effects have been used at one time or another to measure electric current. We now use the magnetic effect in the older type of instruments, but the modern digital meters work on quite different principles.

Working with numbers

We can write any denary number as a number between 1 and 10 multiplied by a **power** of 10. For example, the number 100 is a denary number, equal to 10 tens, and we count in multiples (powers) of 10, using 1000 ($10 \times 10 \times 10$), 10000, 100000 and so on. The number 89 is a denary number, equal to eight tens plus nine units. The number 0.2 is also a denary number equal to 2/10, a decimal fraction. The number 255 can be written as 2.55×100 (or 2.55×10^2) and this is often useful in calculations because it avoids the need to work with numbers that contain a large set of zeros.

A **denary** number is one that is either greater than unity, such as 2, 50 or 350, or a fraction such as 1/10, 3/40 or 7/120 that is made up of digits 0–9 only.

Denary numbers can be added, subtracted, multiplied and divided digit by digit, starting with the least significant figures (the units of a whole number, or the figure farthest to the right of the decimal point of a fraction), and then working left towards the most significant figures.

Decimals are denary numbers that are fractions of 10, so that the number we write as 0.2 means 2/10, and the number we write as 3.414 is 3 + 414/1000. The advantage of using decimals is that we can add, subtract, multiply and divide with them using the same methods as for whole numbers. Even the simplest of calculators can work with decimal numbers.

The numbers 0.047, 47 and 47 000 are all denary numbers. Each of them consists of the two figures 4 and 7, along with a power of 10 which is shown by zeros put in either before or after the decimal point (or where a decimal point would be). The number 0.047 is the fraction 47/1000, and 47 000 is 47 × 1000. The figures 4 and 7 are called the significant figures of all these numbers, because the zeros before or after them simply indicate a power of 10. Zero can be a significant figure if it lies between two other significant figures as, for example, in the numbers 407 and 0.407. The zeros in a number are not significant if they follow the significant figures, as in 370 000, or if they lie between the decimal point and the significant figures, as in 0.000 23.

Powers of 10 are always written in this index form, as shown in Table 1.2. A positive index means that the number is greater than one (unity), and a negative index means that the number is less than unity; for instance, the number $1.2 \times 10^3 = 1200$, the number $47 \times 10^{-2} = 0.047$, and so on.

Table 1.2 Powers of 10 in index form

Number	*Power*	*Written as*
1/1 000 000 or 0.000 001	−6	10^{-6}
1/100 000 or 0.000 01	−5	10^{-5}
1/10 000 or 0.0001	−4	10^{-4}
1/1000 or 0.001	−3	10^{-3}
1/100 or 0.01	−2	10^{-2}
1/10 or 0.1	−1	10^{-1}
1	0	10^{0}
10	1	10^{1}
100	2	10^{2}
1000	3	10^{3}
10 000	4	10^{4}
100 000	5	10^{5}
1 000 000	6	10^{6}

The British Standard (BS) system of marking values of resistance (BS1852/1977) uses the standard prefix letters such as k and M, but with a few changes. The main difference is that the ohm sign (Ω) and the decimal point are **never** used. This avoids making mistakes caused by an unclear decimal point, or by a spot mark mistaken for a decimal point, or the Ω sign mistaken for a zero. This is particularly important for circuit diagrams that are likely to be used in workshop conditions. In this BS system, all values in ohms are indicated by the letter R, all values in kilohms by the letter k, and all values in megohms by M. These letters are then placed where the decimal point would normally be found, and the point is not used. Thus R47 = 0.47

ohms; 5k6 = 5.6 kilohms; 2M2 = 2.2 megohms, and so on. The BS system is illustrated throughout this book. In this system there is no space between the number and the letter. The BS value system is used also for capacitance values and for some voltage values such as the stabilized value of a Zener diode.

Relationships between units

The electrical units of volts, amps and ohms are related, and the relationship is commonly known (not quite correctly) as Ohm's law, which as an equation is written as $V = R \times I$. In words, it means that the voltage measured across a given resistor (in volts) is equal to the value of the resistance (in ohms) multiplied by the amount of current flowing (in amperes). Any equation like this can be rearranged, using a simple rule:

> An equation is unaltered if the quantities on each side of the equals sign are multiplied or divided by the same amount.

For example, the Ohm's law equation can be rearranged, as illustrated in Figure 1.2, as either $R = V/I$ (resistance equals volts divided by current) or $I = V/R$ (current equals volts divided by resistance). We get the first of these by taking $V = R \times I$ and dividing both sides by I to get $V/I = (R \times I)/I$. Because I/I must be 1, this boils down to $V/I = R$ (the same as $R = V/I$). Now try for yourself the effect on $V = R \times I$ of dividing each side by R.

These equations are the most fundamentally important ones you will meet in all your work on electricity and electronics. In electrical circuits the units in which the law has been quoted (volts, amperes, ohms) should normally always be used; but in electronic circuits it is in practice much easier to measure resistance in k and current in mA. Ohm's law can be used in any of its forms when both R and I are expressed in these latter units, but the unit of voltage in these other expressions always remains the volt.

There are, therefore, two different combinations of units with which you can use Ohm's law as it stands: either VOLTS AMPERES OHMS or VOLTS MILLIAMPERES KILOHMS. Never mix the two sets of units. Do not use milliamperes with ohms, or amperes with kilohms. If in doubt, convert your quantities to volts, amps and ohms before using Ohm's law.

Example: What is the resistance of a resistor when a current of 0.1 A causes a voltage of 2.5 V to be measured across the resistor?

Solution: Express Ohm's law in the form in which the unknown quantity R is isolated: $R = V/I$. Substitute the data in units of volts and amperes.

$$R = 2.5/0\ 1 = 25\ \Omega$$

Example: What value of resistance is present when a current of 1.4 mA causes a voltage drop of 7.5 V?

Solution: The current is measured in milliamps, so the answer will appear in kilohms. $R = VI = 7.5/1.4 = 5.36$ kilohms, or about 5k4.

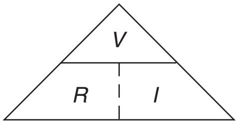
Example: What current flows when a 6k8 resistor has a voltage of 1.2 V across its terminals?

Solution: The data is already in workable units, so substitute in $I = V/R$. Then $I = 1.2/6.8\,\text{A} = 0.176\,\text{A}$, or 176 mA.

Example: What current flows when a 4k7 resistor has a voltage of 9 V across its terminals?

Solution: With the value of the resistor quoted in kilohms, the answer will appear in milliamps. So substitute in $I = V/R$, and $I = 9/4.7 = 0.001\,915\,\text{A} = 1.915\,\text{mA}$.

The importance of Ohm's law lies in the fact that if only two of the three quantities current, voltage and resistance are known, the third of them can always be calculated by using the formula. The important thing is to remember which way up Ohm's law reads. Draw the triangle illustrated in Figure 1.2. Put V at its Vertex, and I and R down below and you will never forget it. The formula follows from this arrangement automatically using a 'cover-up' procedure. Place a finger over I and V/R is left, thus $I = V/R$. The other ratios can be found in a similar way.



$$V = R \times I$$

$$\frac{V}{R} = I$$

$$\frac{V}{I} = R$$

Figure 1.2 The *V R I* triangle

Work, power and energy

The related quantities of work, energy and power are often confused. Mechanical **work** is done whenever a force F causes movement in the same direction as the force through a distance d. The force is measured in units of newtons (N) and 1 N is the force necessary to accelerate a mass of 1 kilogram by 1 metre per second per second ($1\,\text{m/s}^2$). Work is therefore the product of $F \times d$ (measured in newton metres), and this unit is called the **joule**. Work is also directly related to the **torque** or turning moment applied to a rotating shaft. The joule is also the unit of work that is used in electrical measurements.

Power is the rate at which work is done and is measured in **watts** (which are joules of work per second). Work also generates heat and this is also measured in watts. Electric motors were often specified by their work loading in horse power or brake horse power (HP or BHP) on the rating plate, where 1 HP is equivalent to 746 W. Therefore, a 1/2 HP a.c. motor would draw just over 1.5 A from the nominal 240 V supply mains.

Energy is the capacity to do work and, because it is easier to measure power, energy is often calculated as the product of power and time. Thus, 1 J is equal to 1 watt-second (**not** one watt per second but watts multiplied by seconds). This means that 1 kWh = 3600 kilojoules (kJ) or 3.6 megajoules (MJ).

When a current flows through a resistor, electrical energy is converted into heat energy, and this heat is passed on to the air around the resistor, and dissipated, spread around. The rate at which heat is dissipated, which is the rate of working, is **power**, and is measured in units of watts.

The amount of power dissipated can be calculated from any two of the quantities V (in volts), I (in amps) and R (in ohms), as follows:

• Using V and I	Power = $V \times I$ watts
• Using V and R	Power = V^2/R watts
• Using I and R	Power = I^2R watts

Most electronic circuits use small currents measured in mA, and large values of resistance measured in k, and we seldom know both volts and current. The power dissipated by a resistor is therefore often more conveniently measured in milliwatts using volts and k or using milliamps and k. Expressing the units V in volts, I in milliamps and W in milliwatts, the equations to remember become:

The milliwatts dissipated = V^2/R (using volts and k)
= I^2R (using milliamps and k)

Example: How much power is dissipated when: (a) 6 V passes a current of 1.4 A, (b) 8 V is placed across 4 ohms, (c) 0.1 A flows through 15 R?

Solutions: (a) Using $V \times I$, Power = $6 \times 1.4 = 8.4$ W, (b) using V^2/R, Power = $8^2/4 = 64/4 = 16$ W, (c) using I^2R, Power = $0.1^2 \times 15 = 0.01 \times 15 = 0.15$ W.

Example: How much power is dissipated when (a) 9 V passes a current of 50 mA, (b) 20 V is across a 6k8 resistor, (c) 8 mA flows through a 1k5 resistor?

Solutions: (a) Using $V \times I$, Power = $9 \times 50 = 450$ mW, (b) using V^2/R, Power = $20^2/6.8 = 400/6.8 = 58.8$ mW, (c) using I^2R, Power = $8^2 \times 1.5 = 64 \times 1.5 = 96$ mW.

The amount of energy that is dissipated as heat is measured in joules. The watt is a rate of dissipation equal to the energy loss of one joule per second, so that joules = watts × seconds or watts = joules/second. The energy is found by multiplying the value of power dissipation by the amount of time during which the dissipation continues. The resulting equations are: Energy dissipated = $V \times I \times t$ joules or V^2t/R joules or I^2Rt joules, where t is the time during which power dissipation continues, measured in seconds. In electronics you seldom need to make use of joules except in heating problems, or in calculating the stored energy of a capacitor.

Electrical components and appliances are rated according to the power that they dissipate or convert. A 3 W resistor, for example, will dissipate 3 J of energy per second; a 3 kW motor will convert 3000 J of energy per second into motion (if it is 100% efficient). As a general rule, the greater the power dissipation required, the larger the component needs to be.

Calculations

At one time tables of values were used to help in solving complicated calculations, or calculations that used numbers containing many **significant figures**. Significant figures are the digits that need to be used in calculations, so that zeros ahead of or following other digits are not significant, but zeros between other digits are. For example, the zeros in 12 000 or 0.0053 are not significant because it is only the other digits, the 1 and 2 or 5 and 3, that we really need to work with. When you multiply 12 000 by 3, you don't need to start by thinking 'three times zero is zero, three times zero is zero' and so on. You simply think 'three times 12 (thousand) is 36 (thousand)'. Zeros in 26 005 **are** significant because they are part of the number.

Nowadays we use electronic calculators in place of tables, but a calculator is useful only if you know how to use it correctly. Calculators can be simple types that can carry out addition, subtraction, multiplication and division only, and these can be useful for most of your calculations.

To solve some of the other types of calculations you will meet in the course of electronics servicing, a scientific calculator is more useful. A good scientific calculator, such as the Casio, need not be expensive and it will be able to cope with any of the calculations that will need to be made throughout this course. You should learn from the manual for your calculator how to carry out calculations involving squares, square roots and powers, angle functions (particularly sines and cosines), and the use of brackets.

The **square** of a number means that number multiplied by itself. For example, 2 squared (written as 2^2) is $2 \times 2 = 4$. Five squared is 25. It is simple enough for whole numbers, but when it comes to numbers with fractions, like 6.75^2 (equal to 45.5625), then you need a calculator.

Many of the quantities used in electronics measurements are **ratios**, such as the ratio of the current flowing in the collector circuit of a transistor (I_c) to the current flowing in its base circuit (I_b). A ratio consists of one number divided by another, and can be expressed in several different ways:

- as a common fraction, such as 2/25
- as a decimal fraction, such as 0.47; this is the most common method
- as a percentage, such as 12% (which is another way of writing the fraction 12/100).

To convert a decimal fraction into a common fraction, first write the figures of the decimal, but not the point. For example, write 0.47 as 47. Now draw a fraction bar under this number (called the **numerator**) and under it write a power of 10 with as many zeros as there are figures above. In this example, you would use 100, with two zeros because there are two digits in 47. This makes the fraction 47/100.

To convert a common fraction into a decimal, do the division using a calculator. For example, the fraction 2/27 uses the 2, division and 27 keys and comes out as 0.074 074, which you would round to 0.074.

To convert a decimal ratio into a percentage, shift the decimal point two places to the right, so that 0.47 becomes 47%. If there are empty places, fill them with zeros, so that 0.4 becomes 40%.

To convert a percentage to a decimal ratio, imagine a decimal point where the % sign was, and then shift this point two places to the left, so that 12% becomes 0.12. Once again, empty places are filled with zeros, so that 8% becomes 0.08.

Averages

The **average value** of a set of numbers is found by adding up all the numbers in the set and then dividing by the number of items in the set. Suppose that a set of resistors has the following values: one 7R, two 8R, three 9R, four 10R, four 11R, three 12R and two 13R. This is a set of 19 values, and the average value of the set is found as follows:

$$\frac{\left[\begin{array}{l}7+8+8+9+9+9+10+10+10+10+\\ 11+11+11+11+12+12+12+13+13\end{array}\right]}{19}=\frac{196}{19}$$

This divides out to 10.32 (using two places of decimals), so that the average value of the set is 10.32 ohms or 10R32.

An average value like this is often not ‘real’, in the sense that there is no actual resistor in the set that has the average value of 10.32R. It is like saying that the average family size in the UK today is 2.2 children. This may be a perfectly truthful average value statement, but you will seldom meet a family containing two children and 0.2 of a third one.

Chemical cells

Cells convert chemical energy into d.c. electrical energy without any intermediate stage of conversion to heat. Only a few chemical reactions can at present be harnessed in this way, although work on fuel cells has enabled electricity to be generated directly without any fuel having to be burned to provide heat. Cells and batteries, however, although important as a source of electrical energy for electronic devices, represent only a tiny (and expensive) fraction of the total electrical energy that is generated.

A cell converts chemical energy directly into electrical energy. A collection of cells is called a **battery**, but we often refer to a single cell as a ‘battery’. Cells may be connected in **series** to increase the voltage available or in **parallel** to increase the current capacity, but parallel connection is usually undesirable because it can lead to the rapid discharge of all cells if one becomes faulty and the others pass current into the faulty cell.

Cells may be either primary or secondary cells. A **primary cell** is one that is ready to operate as soon as the chemicals composing it are put together.

Once the chemical reaction is finished, the cell is exhausted and can only be thrown away. A **secondary cell** generally needs to be charged by connecting it to a voltage higher than the output voltage of the cell before it can be used. Its chemical reaction takes place in one direction during charging, and in the other direction during discharge (use) of the cell. The cell can then be recharged.

Cells are classed according to their open-circuit voltage (usually 1.2–1.6 V, except for lithium cells) and their capacity. **Open circuit** means that nothing is connected to the cell that could allow current to flow. The **capacity** of a cell is its stored energy, measured in mA-hours. In principle, a cell rated at 500 mA-hours could supply 1 mA for 500 hours, 2 mA for 250 hours, 10 mA for 50 hours, and so on. In practice, the figure of energy capacity applies for small discharge currents and is lower when large currents are delivered.

Cells also have **internal resistance**, the resistance of the current-carrying chemicals and conducting metals in the cell. This limits the amount of current that the cell can deliver to a load, because even if the cell is short-circuited the internal resistance will limit the amount of current. Rechargeable cells usually have lower values of internal resistance than the non-rechargeable type.

Most primary cells are of the zinc/carbon (Leclanché) type, of which a cross-section is shown in Figure 1.3. The zinc case is sometimes steel coated to give extra protection. The ammonium chloride paste is an acidic material which gradually dissolves the zinc. This chemical action provides the energy from which the electrical voltage is obtained, with the zinc the negative pole.

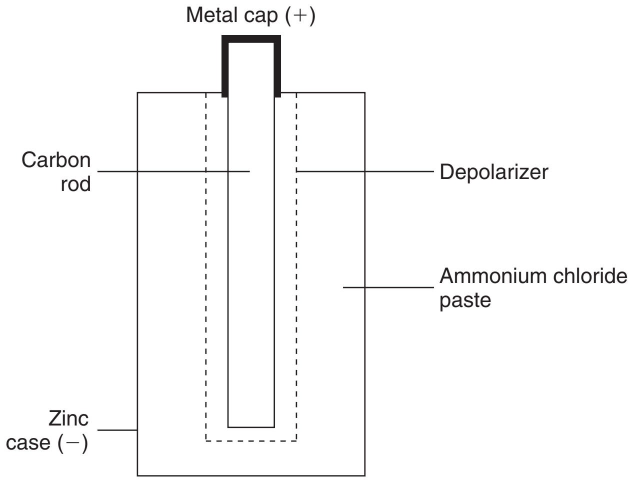


Figure 1.3 A typical (Leclanché) dry cell construction

The purpose of the manganese dioxide *depolarizer* mixture that surrounds the carbon rod is to absorb hydrogen gas, a by-product of the chemical reaction. The hydrogen would otherwise gather on the carbon, insulating it so that no current could flow. The zinc/carbon cell is suitable for most purposes for which batteries are used, having a reasonable shelf-life and yielding a fairly steady voltage throughout a good working life.

Other types of cell such as alkaline manganese, mercury or silver oxide and lithium types are used in more specialized applications that need high working currents, very steady voltage or very long life at low current drains. However, mercury-based cells are not considered environmentally friendly when discarded unless they can be returned to the manufacturer. The use of a depolarizer is needed only if the chemical action of the cell has generated hydrogen, and some cell types do not.

Practical 1.1

Connect the circuit of Figure 1.4(a) using a 9 V transistor radio battery. Draw up a table on to which readings of output voltage *V* and current *I* can be entered.

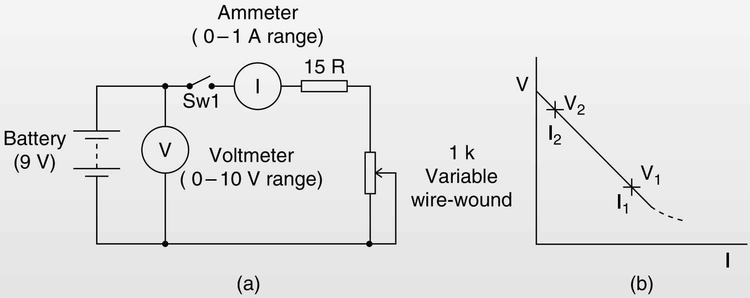


Figure 1.4 (a) Circuit for Practical 1.1, and (b) graph

With the switch Sw1 open, note the voltmeter reading (using the 10 V scale). Mark the current column ‘zero’ for this voltage reading. Then close Sw1 and adjust the variable resistor until the current flow recorded on the current meter is 50 mA. Note the voltage reading *V* at this level of current flow, and record both readings on the table. Open switch Sw1 again as soon as the readings have been taken.

Go on to make a series of readings at higher currents (75 mA, 100 mA, etc.) until voltage readings of less than 5 V are being recorded. Take care that for every reading Sw1 remains closed for only as long as is needed to make the reading. Plot the readings you have obtained on a graph of output voltage against current. It should look like the example shown in Figure 1.4(b).

(Continued)

Practical 1.1 (Continued)

Now pick from the table a pair of voltage readings $V1$ and $V2$, with $V2$ greater than $V1$, together with their corresponding current readings, $I1$ and $I2$, expressed in amperes. Work out the value of the expression shown, left, and you will get the internal resistance of the battery in units of ohms.

Note that false readings can be obtained if a cell passes a large current for more than a fraction of a second. Try to make your readings quickly when you are using currents approaching the maximum, and switch off the current as soon as you have taken a reading.

Most primary cells have an open-circuit voltage (or emf) of around 1.4–1.5 V. The important exception is the lithium cell (see later), which provides around 3.5 V. A lithium cell must **never** be opened, because lithium will burst into flames on exposure to air or water. Lithium cells should not be recharged or put into a fire.

Towards the end of the useful life of a cell or battery, the value of its internal resistance rises. This causes the output voltage at the terminals of the cell or battery to drop below its normal value when current flows through the cell or battery, which is then said to have poor **regulation**. A voltage check with this cell or battery removed from the equipment will show a normal voltage rating, but the cell or battery should nevertheless be replaced.

The only useful check on the state of a cell or battery is a comparison of voltage reading on load (with normal current flowing) with the known on-load voltage of a fresh cell. Simply reading the voltage of a cell that is not connected to a load is pointless.

At one time, the term **secondary cell** meant either the type of lead-acid cell which is familiar as the battery in a car, or the nickel–iron alkaline (NiFe) cell used in such applications as the powering of electric milk floats. In present-day electronics, both types have to some extent been superseded by the nickel–cadmium (NiCd or nicad), nickel–metal-hydride (Ni-MH) and lithium-ion secondary (meaning rechargeable) cells. There is, however, a large difference in the emf of secondary cells. The old lead-acid type has an emf of 2.0 V (2.2 V when fully charged), but the nickel–cadmium and Ni-MH types have a much lower emf of only 1.2 V, and the lithium-ion cell can provide around 3.6 V.

The NiCd cell uses as its active material cadmium (a metal like zinc), in powdered form, that is pressed or sintered into perforated steel plates, which then form the negative pole of the cell. The positive pole is a steel mesh coated with solid nickel hydroxide. The electrolyte is potassium hydroxide (caustic potash), usually in jelly form (Figure 1.5).

Nickel–cadmium (nicad) cells are sealed so that no liquids can be spilled from them, and they have a fairly long working life provided they are correctly used. They can deliver large currents, so they can be used for

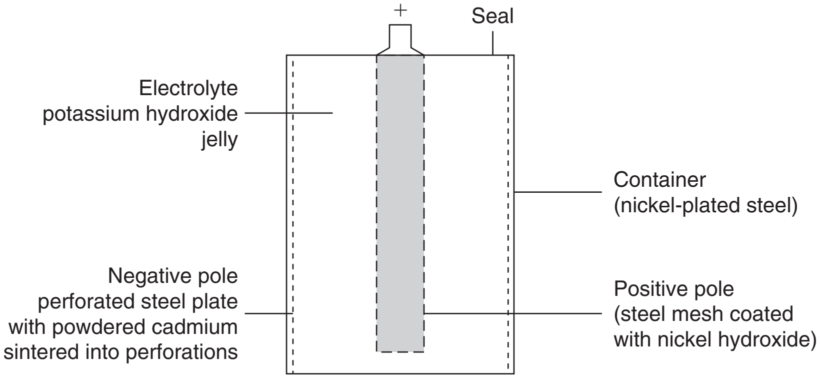


Figure 1.5 The nickel–cadmium cell

equipment that demands higher power than could be supplied by primary cells. They have much longer life than other cells in applications for which they are rapidly discharged at intervals. Long periods of inactivity can cause the cells to fail, although it is often possible to restore their action by successive cycles of discharging and charging. One major problem is the memory effect, a reduction in capacity caused by recharging before the cell is fully discharged. Because of this, it is common practice to use a discharging cycle before charging a nickel–cadmium cell.

More recently, the sealed Ni-MH battery has been introduced. This type has up to 40% higher capacity than its nickel–cadmium counterpart of the same size, and also offers benefits of faster charge and discharge rates, and longer life. The Ni-MH cell contains no cadmium and is therefore more environmentally acceptable. The operating voltage is about the same as that of the NiCd cell. The memory effect can be greatly reduced if the Ni-MH battery is on occasions completely discharged before recharging. The usual recommendation is that this should be done after three to five normal charge–discharge sequences.

Table 1.3 shows the advantages and disadvantages of using batteries as power sources for electronic equipment, as compared to mains supplies.

Table 1.3 Battery-operated equipment

Advantages	*Disadvantages*
Equipment is portable	Limited energy capacity
An ordinary battery is smaller and lighter than is any form of connection to the main supply	Voltage generally low
Safer to use, no high voltages being involved	Batteries deteriorate during storage
Equipment requires no trailing leads	Batteries for high voltage or high current operation are heavier and more bulky than the equivalent mains equipment

Lithium-ion rechargeable cell

The lithium-ion rechargeable (Li-ion) cell avoids the direct use of the metal lithium because it oxidizes too readily. A lithium-ion cell must never be broken open. The carbon anode is formed from a mixture of compounds at about 1100°C and then electrochemically treated with a lithium compound. The cathode is formed from a mixture of the compounds of lithium, cobalt, nickel and manganese. A mixture of chemicals, avoiding the use of water, is used for the electrolyte. This cell is nominally rated at 3.6 V and has a long self-discharge period, typically falling by 30% after 6 months. The recharge period is typically about 3 hours and the cell can withstand at least 1200 charge–recharge cycles.

In addition to its advantages with holding increased energy, the Li-ion cell tends not to suffer from the memory effect, ensuring a longer life even when poorly treated. Its features include high energy density and high output voltage with good storage and cycle life. Lithium-ion cells are used in desktop personal computers (to back up memory), camcorders, cellular phones and also for portable compact disc (CD) players, laptop computers, personal digital assistants (PDAs) and similar devices. Lithium-ion cells have even been used in an electric sports car (the Venturi Fetish).

The cell operates on the principle that both charging and discharging actions cause lithium ions to transfer between the positive and negative electrodes. Unlike the action of other cells, the anode and cathode materials of the lithium-ion cell remain unchanged through its life.

Charging cells

Lead-acid cells need to be recharged from a constant-voltage supply, so that when the cell is fully charged, its voltage is the same as that of the charger, and no more current passes. By contrast, nickel–cadmium cells must be charged at constant **current**, with the current switched off when the cell voltage reaches its maximum. Constant-current charging is needed so that excessive current cannot pass when the cell voltage is low. Using the wrong charging method can damage cells.

Nickel–metal-hydride cells need a more complicated charger circuit, and one typical method charges at around 10% of the maximum rate, with the charging ended after a set time. A charger suitable for Ni-MH cells can be used also for NiCd, but the opposite is not true. Some types of cell include a temperature sensor that will open-circuit the cell when either charge or discharge currents cause excessive heating. For some applications trickle charging at 0.03% of maximum can be used for an indefinite period.

Lithium-ion cells can be charged at a slow rate using trickle-chargers intended for other cell types, but for rapid charging they require a specialized charger that carries out a cycle of charging according to the manufacturer's instructions.

A completely universal battery charger needs to be microprocessor controlled and is an expensive item, although useful if you use a variety of different cells.

Table 1.4 compares primary and secondary cells.

Table 1.4 Primary and secondary cells compared

Primary cells	*Secondary cells*
Low cost	Expensive
Small size	Some fairly large
Short life	Comparatively long life
Throw away when exhausted	Rechargeable
Light weight	Generally heavier than equivalent primary cell
Readily available	Specialized products, less easily obtainable

Capacitors with a value of about 1–5 farads (F), which can be charged to 5 V through a high value of resistance, can support a small (backup) discharge current for many hours. Modern construction provides a device of only about 5 mm high with the same diameter, so that these can be used to provide a backup power supply for circuits that need only a small current to maintain operation throughout short duration power failures.

Connecting cells

When a set of cells is connected together, the result is a **battery**. The cells that form a battery could be connected in series, in parallel, or in any of the series–parallel arrangements, but in practice the connection is nearly always in series. The effect of both series and parallel connection can be seen in Figure 1.6. When the cells are connected in series, the open-circuit voltages (emfs) add, and so do the internal resistance values, so that the overall voltage is greater, but the current capability is the same as that of a single cell.

When the cells are connected in parallel, the voltage is as for one cell, but the internal resistance is much lower, because it is the result of several internal resistances in parallel. This allows much larger currents to be drawn, but unless the cells each produce *exactly* the same emf value, there is a risk that current will flow between cells, causing local overheating. For this reason, primary cells are never used connected in parallel, and even secondary cells, which are more able to deliver and to take local charging current, are seldom connected in this way.

Higher currents are therefore obtained by making primary cells in a variety of (physical) sizes, with the larger cells being able to provide more current, and having a longer life because of the greater quantity of essential chemicals. The limit to size is portability, because if a primary cell is not portable it has a limited range of applications. Secondary cells have much

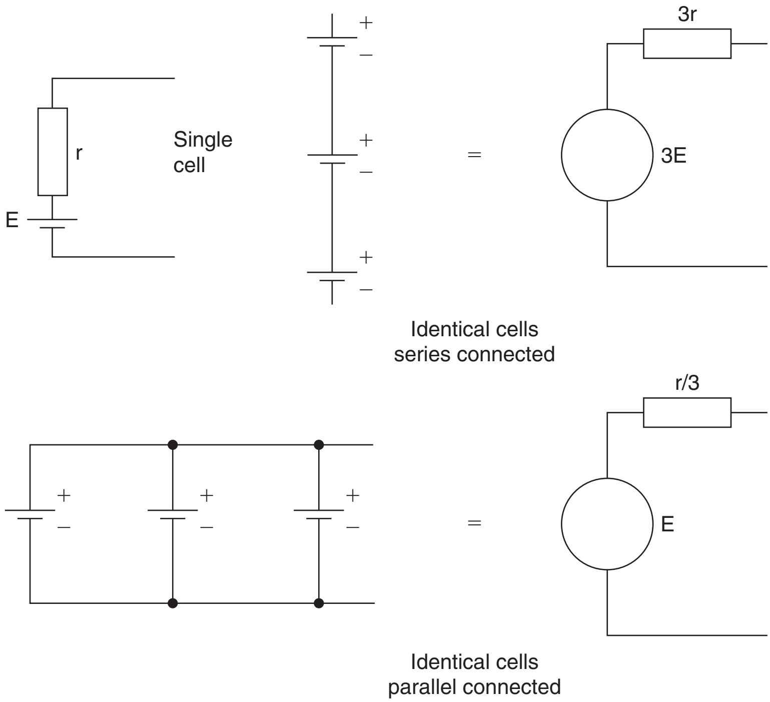


Figure 1.6 Connecting cells in series and in parallel

lower internal resistance values, so that if high current capability is required along with small volume, a secondary cell is always used in preference to a primary cell. One disadvantage of the usual type of nickel–cadmium secondary cell in this respect, however, is a short *shelf-life*, so that if equipment is likely to stand for a long time between periods of use, secondary cells may not be entirely suitable, because they will always need to be recharged just before use.

The important parameters for any type of cell are its open-circuit voltage (the emf), its 'typical' internal resistance value, its shelf-life, active life and energy content. The **internal resistance** is the resistance of the electrolyte and other conductors in the cell, and its value limits the amount of current that a cell can provide because it causes the output voltage of the cell to drop when current flows. The **shelf-life** indicates how long a cell can be stored, usually at a temperature not exceeding 25°C, before the amount of internal chemical action seriously decreases the useful life. The **active life** is less easy to define, because it depends on the current drain, and it is usual to quote several figures of active life for various average current drain values. The **energy content** is defined as emf × current × active life, and will usually be calculated from the most favourable product of current and time. The energy content is affected more by the type of chemical reaction and the weight of the active materials than by details of design.

Multiple-choice revision questions

1.1 The quantity ‘voltage’ measures:
- (a) flow of electric current
- (b) quantity of electric current
- (c) driving force of electric current
- (d) stored electric current.

1.2 In the number 537, the digit 7 is:
- (a) a binary digit
- (b) the least significant digit
- (c) the most significant digit
- (d) a decimal fraction.

1.3 The prefix M means:
- (a) one hundred
- (b) one thousand
- (c) ten thousand
- (d) one million.

1.4 When a potential difference of 6 V exists across a 1k0 resistor, the current flowing will be:
- (a) 6 mA
- (b) 3 A
- (c) 0.16 A
- (d) 1/6 mA.

1.5 A cell or a battery converts:
- (a) heat energy into electrical energy
- (b) electrical energy into light energy
- (c) electrical energy into chemical energy
- (d) chemical energy into electrical energy.

1.6 A nickel–cadmium (NiCd) cell must be recharged:
- (a) from a source of constant current
- (b) from a low-impedance source
- (c) from a source of constant voltage
- (d) from a high-impedance source.

2

Conductors, insulators, semiconductors and wiring

Conductors and insulators

Conductors are materials that allow a steady electric current to flow easily through them, and which can therefore form part of a circuit in which a current flows. All metals are good conductors. Gases at low pressure (as in neon tubes) and solutions of salts, acids or alkalis in water will also conduct electric current well.

Insulators are materials that do not allow a steady electric current to flow through them and they are therefore used to prevent such a flow. Most of the insulators that we use are solid materials that are not metals. Natural insulators, such as sulphur and pitch, are no longer used, and plastic materials such as polystyrene and polythene have taken their place. Pure water is an insulator, but any trace of impurity will allow water to conduct some current, so that this provides one way of measuring water purity.

Semiconductors are materials whose ability to conduct current can be enormously changed by adding microscopic amounts of chemical elements. In a pure state, a semiconductor is an insulator, although light or high temperature will greatly lower the resistance.

A good example of the contrasting uses of insulators and conductors is provided by printed circuit boards. The boards are made of an insulator, typically stiff bonded paper called SRBP (synthetic-resin bonded paper), which is impregnated with a plastic resin; but the conducting tracks on the boards are made of conducting copper or from metallic inks. Boards made from fibreglass are used for more demanding purposes.

Both *insulation and conduction* are relative terms. A conductor that can pass very small currents may not conduct nearly well enough to be used with large currents. An insulator that is sufficient for the low voltage of a torch cell could be dangerously unsafe if it were used for the voltage of the mains (line) supply.

Resistance

The amount of conduction or insulation of materials is measured by their **resistance**. A very low resistance means that the material is a conductor; a very high resistance means that the material is an insulator. The resistance of any sample of a substance measures the amount of opposition it presents to the flow of an electric current. A long strip of the material has more resistance than a short strip of the same material. A wide sample has less resistance than a narrow sample of the same length and same material. These effects are illustrated in Figure 2.1.