CHAPTER

8

Transmission of power


Transformers at a substation

REMEMBER

Before beginning this chapter, you should be able to:

- determine the amount of magnetic flux passing through an area
- determine the average induced voltage in a loop from the flux change and the time in which the change took place
- describe and determine the following properties of an AC voltage: frequency, period, amplitude, peak-to-peak voltage, peak-to-peak current, RMS voltage and RMS current
- describe the relationship between charge, current, voltage energy and power in electric circuits
- use the formulae $Q = It$, $E = VQ$, $E = VIt$, $P = VI$, $V = IR$ and $P = I^2R$.

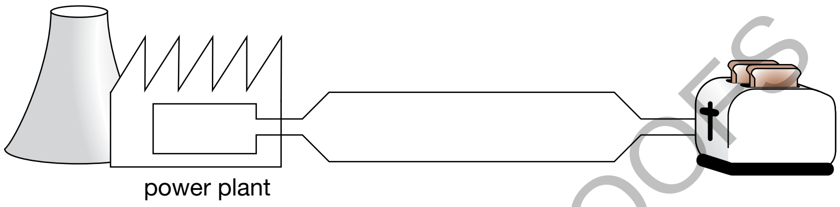
KEY IDEAS

After completing this chapter, you should be able to:

- explain the operation of a transformer in terms of electromagnetic induction
- determine the voltage and current using the number of turns in the primary and secondary coils, assuming the transformer is ideal
- determine transmission losses using $V_{\text{drop}} = I_{\text{line}}R_{\text{line}}$ and $P_{\text{loss}} = I_{\text{line}}^2R_{\text{line}}$
- explain the use of transformers in an electricity distribution system
- explain the advantage of AC power as a domestic power supply.

Electric power

Electric power is generated for a purpose — to provide lighting in streets and homes, and to operate motors in domestic and industrial appliances. But electric power is often generated very far from where it is consumed. This problem *appears* to be simply overcome: make the connecting wires from the generator to the light or motor longer and longer, even stretching to hundreds of kilometres, and you have your basic transmission line.



Why not just extend the wires from your toaster all the way back to the power plant generator?

This simple solution might work on the laboratory bench where the connecting wires are so short that their resistance is a very small fraction of the overall resistance in the circuit. However, when the wires extend over kilometres, their resistance becomes significant. So, too, does the power loss in them because of the I^2R heating effect of the current. In addition, so much of the supply voltage now drops along the wires, that the remaining voltage across the devices is insufficient for them to operate properly. However, this power loss and voltage drop can be reduced with the use of transformers.

Sample problem 8.1

A 100 W light globe uses 100 J of energy every second when the voltage across it is 230 V.

(a) Calculate the current through the globe.
(b) Calculate the resistance of the globe for this current and voltage.
(c) (i) If the globe was connected to a 230 V power supply by 2.0 m of copper wire, what would be the total resistance of the circuit? The wire has a resistance of $0.022\ \Omega\,\text{m}^{-1}$.
    (ii) What would be the voltage across the globe?
(d) (i) If the globe was connected by 100 km of copper wire, what would be the total resistance of the circuit?
    (ii) What would be the voltage across the globe now?
(e) Comment on how the light globe would respond.

Solution: (a) $P = 100\ \text{W},\ V = 230\ \text{V}$

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

$$I = 0.435\ \text{A} \qquad \text{(0.43 A to two significant figures)}$$

The current through the globe is 0.43 A.

(b)
$$\begin{aligned} R &= \frac{V}{I} \\ &= \frac{230\ \text{V}}{0.435\ \text{A}} \\ &= 529\ \Omega \qquad \text{(530 }\Omega\text{ to two significant figures)} \end{aligned}$$

The resistance of the globe is 530 Ω.

(c) (i) $$\begin{aligned}R_{\text{total}} &= R_{\text{copper}} + R_{\text{globe}}\\ &= (2.0\,\text{m} \times 0.022\,\Omega\,\text{m}^{-1}) + 529\,\Omega\\ &= 529\,\Omega \text{ to one decimal point}\\ &\quad (530\,\Omega \text{ to two significant figures})\end{aligned}$$

The total resistance of the circuit is 530 Ω.

(ii) $$\begin{aligned}V &= \frac{R_{\text{globe}}}{R_{\text{total}} \times 230\,\text{V}}\\ &= \frac{529\,\Omega}{529\,\Omega \times 230\,\text{V}}\\ &= 230\,\text{V}\end{aligned}$$

The voltage across the globe is 230 V.

(d) (i) $$\begin{aligned}R_{\text{total}} &= R_{\text{copper}} + R_{\text{globe}}\\ &= (100 \times 10^{3}\,\text{m} \times 0.022\,\Omega\,\text{m}^{-1}) + 529\,\Omega\\ &= 2729\,\Omega \text{ to the nearest whole number}\\ &\quad (2700\,\Omega \text{ to two significant figures})\end{aligned}$$

The total resistance of the circuit is 2700 Ω.

(ii) $$\begin{aligned}V &= \frac{R_{\text{globe}}}{R_{\text{total}} \times 230\,\text{V}}\\ &= \frac{529\,\Omega}{2729\,\Omega \times 230\,\text{V}}\\ &= 45\,\text{V}\end{aligned}$$

The voltage across the globe is 45 V.

(e) The globe would not light up.

Transformers

The transmission line transmits electrical energy from generator to appliance. The electrical energy is generated at a voltage set by the generator. The current drawn from the generator depends on the resistance in the appliances connected to the generator. Appliances are connected in parallel, so that they can all have the same voltage. Plugging in additional appliances is the same as adding extra resistances in parallel, with each appliance drawing its own current from the supply. The extra appliances in parallel reduce the total resistance in the circuit.

With more appliances connected, there is a larger current drawn from the generator and therefore greater energy supplied. The amount of energy supplied by the generator every second, or electrical power supplied, is equal to the product of the voltage supplied by the generator and the current drawn from the generator.

If the transmission lines are long, the energy wasted due to their resistance becomes a significant fraction of the energy supplied by the generator. If the same amount of energy every second (that is, the same power) can be sent along the lines but at a lower current, the energy loss will be less. In fact, since the power loss is given by I^2R (current^2 × resistance of the lines), if the current through the lines is halved, the power loss is reduced by a quarter.

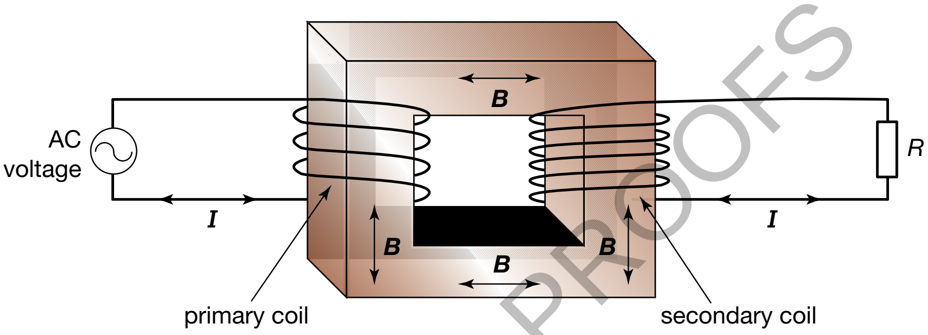
In 1831 Michael Faraday constructed a device to achieve this when he demonstrated that an electric current in one circuit had a magnetic effect that could produce an electric current in another circuit.

Faraday's **transformer** consisted of two sets of coils of wire wrapped around a ring of iron. One coil was connected to a battery by a switch, the other to a galvanometer, a sensitive current detector.

A **transformer** is a device in which two multi-turn coils are wound around an iron core. One coil acts as an input while the other acts as an output. The purpose of the transformer is to produce an output AC voltage that is different from the input AC voltage.

As with other examples of electromagnetic induction, the transformer works only when there is a change in magnetic flux in the coils and the connecting iron core.

With a battery connected to the primary coil, the secondary coil has a current only when the switch in the primary coil is either opening or closing. To produce a continuous current in the secondary coil, the current in the primary coil needs to be continually changing. The obvious candidate is AC current, but an AC generator was not developed until 1881 by Lucien Gaulard and John D. Gibbs.



A changing current, ***I***, in the primary coil produces a changing magnetic field, ***B***, in the iron core, which is propagated through the iron core to the secondary coil, where the changing magnetic field induces a changing emf in the secondary coil.

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How does a transformer work?

Imagine an iron core shaped as a square. Around two sides are coils of wire. If an AC voltage is applied to the primary coil, an alternating magnetic field will be set up in the iron core. This alternating magnetic field will propagate through the iron core to the secondary coil. Here, the alternating magnetic field will induce an alternating voltage in this coil of the same frequency as the primary AC voltage.

An AC voltage supplied to the primary coil produces an AC voltage at the secondary coil, even though there is no electrical connection between the two coils. How do the sizes of the two voltages compare? In other words, how do the RMS voltages compare?

Comparing voltages

When an AC voltage supply, V_{prim}, is connected to the primary coil, the current will be limited by the resistance in the coil — which will be proportional to the number of turns, N_{prim}, in the coil.

The iron core has constantly changing magnetic flux throughout. So, applying Faraday's Law:

to the primary coil gives

$$V_{\text{prim}} = N_{\text{prim}} \times \frac{\Delta \Phi_{\text{B}}}{\Delta t}$$

and to the secondary coil gives

$$V_{\text{sec}} = N_{\text{sec}} \times \frac{\Delta \Phi_{\text{B}}}{\Delta t}.$$

Rearranging gives

$$\frac{\Delta \Phi_{\text{B}}}{\Delta t} = \frac{V_{\text{prim}}}{N_{\text{prim}}} = \frac{V_{\text{sec}}}{N_{\text{sec}}}$$

or

$$\frac{V_{\text{prim}}}{V_{\text{sec}}} = \frac{N_{\text{prim}}}{N_{\text{sec}}}.$$

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Concept 1

Transformers — how they work
Summary screen and practice questions

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Unit 3
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Concept 2

Transformers — voltage and turns ratios
Summary screen and practice questions

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Do more
Transforming voltage and current

A **step-up transformer** produces an output (secondary) voltage that is greater than the input (primary) voltage.

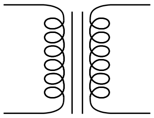
A **step-down transformer** produces an output (secondary) voltage that is less than the input (primary) voltage.

This relationship means that two types of transformer can be built. One type, which produces a secondary voltage greater than the primary, is called a **step-up transformer**. In this, the number of secondary turns is greater than the number of primary turns.

The other type is a **step-down transformer**, which features more primary turns than secondary turns. It produces a smaller secondary voltage than the primary voltage. Both types are used in the distribution of electricity from generator to home, and also inside the home.

AS A MATTER OF FACT

Low-voltage lighting is now quite common in instances where 230 V AC would present a safety risk (for example, Christmas tree lights or external garden lighting). In these cases, a step-down transformer converts the 230 V AC down to a safer 12 V AC.



Circuit diagram symbol for transformer

If there is no energy loss as the energy is transferred from the primary to the secondary side, then the *power in* to the primary coil will equal the *power out* of the secondary coil. Since power = voltage × current, this can be written as:

$$V_{\text{prim}} \times I_{\text{prim}} = V_{\text{sec}} \times I_{\text{sec}}.$$

Using this relationship, the main design characteristics of any transformer can be determined.

Sample problem 8.2

A step-down transformer is designed to convert 230 V AC to 12 V AC. If there are 190 turns in the primary coil, how many turns are in the secondary coil?

Solution: $V_{\text{prim}} = 230\text{ V}, V_{\text{sec}} = 12\text{ V}, N_{\text{prim}} = 190\text{ turns}, N_{\text{sec}} = ?$

$$\frac{V_{\text{prim}}}{N_{\text{prim}}} = \frac{V_{\text{sec}}}{N_{\text{sec}}}$$

$$\frac{230\text{ V}}{190\text{ turns}} = \frac{12\text{ V}}{N_{\text{sec}}}$$

$$N_{\text{sec}} = 12\text{ V} \times \frac{190\text{ turns}}{230\text{ V}}$$

$$= 9.9\text{, approximately 10 turns}$$

Revision question 8.1

A generator supplies 10 kW of power to a transformer at 1.0 kV. The current in the secondary coil is 0.50 A. What is the turns ratio of the transformer? Is it a step-up or a step-down transformer?

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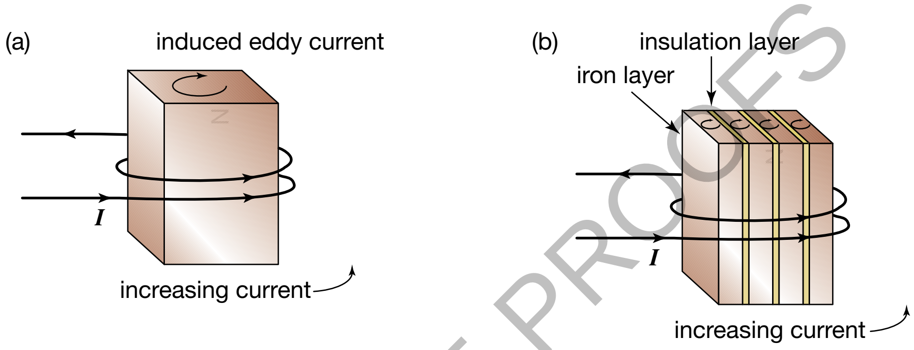
Ideal versus real

All transformers lose some energy in transferring electric power from the primary side to the secondary. This energy loss occurs in two areas. The first area is in the wires that make up the primary and secondary coils. This loss is called either *copper loss* (because the wires are usually copper), or *resistive* or I^2R *loss*. The loss is usually quite minor. If the transformer is being designed to take large currents, the wires on that side would be made thicker to take the high current and minimise the resistance.

The other area of energy loss in the transformer is in the iron core. The loss is due to induced currents in the iron core. These currents are called **eddy currents**, because they are like the swirls, or eddies, left in the water after a boat has gone by.

An **eddy current** is an electric current induced in the iron core of a transformer. Eddy currents result in undesirable energy losses from the transformer.

The changing magnetic flux in the iron core produces a changing voltage in each of the turns of the secondary coils. Iron is an electrical conductor, so it will behave in the same way as the turns of wire. A circular current will be induced in the iron in a plane at right angles to the direction of the changing magnetic flux.



(a) An eddy current induced in an iron core by a changing magnetic field, and (b) putting the iron core into layers reduces the currents.

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See more
Electricity distribution system

If the iron core was one solid piece of iron, these induced eddy currents would be quite substantial. As iron has a low resistance, it would lead to large energy loss.

To minimise this loss, the iron core is constructed of layers of iron sandwiched between thin layers of insulation. These layers, called laminations, significantly reduce the energy loss. In practice, transformers used to transmit large quantities of energy are about 99% efficient.

Transmission lines and towers near Melbourne

Power distribution and transmission line losses

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Transmission lines and power loss
Summary screen and practice questions

study on

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Do more
Losing power

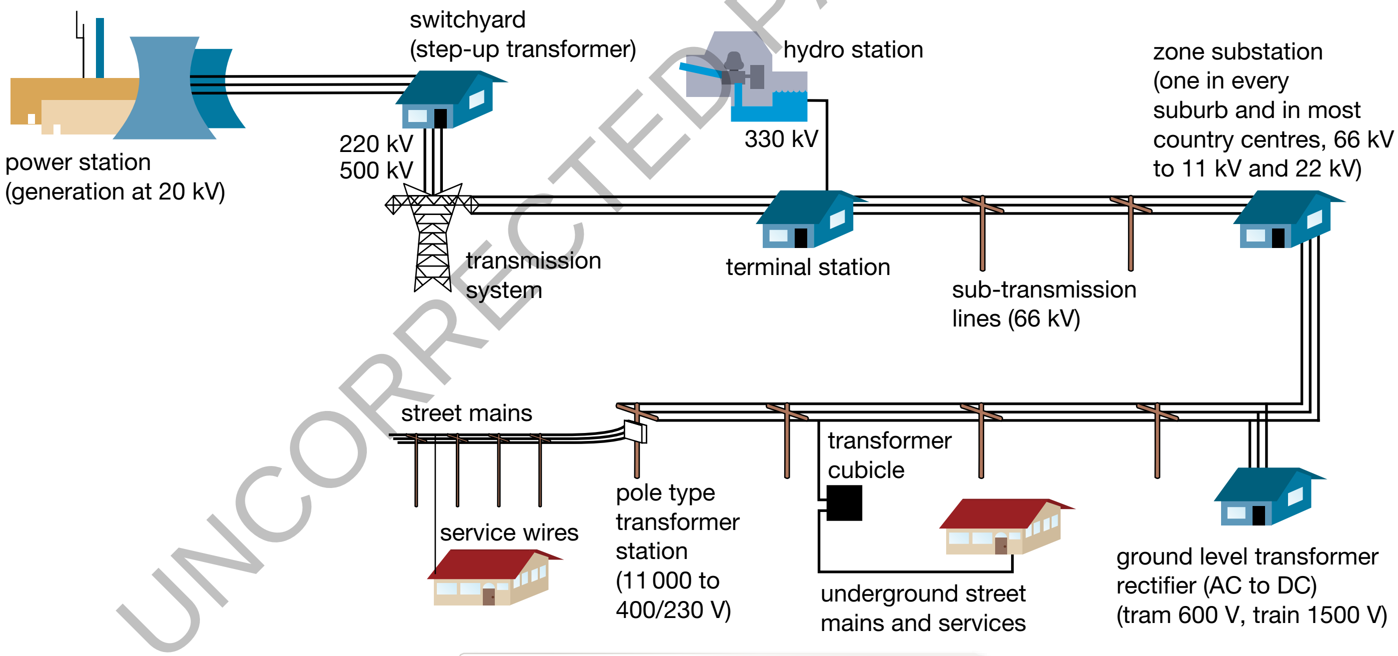
Development of the transformer meant that the AC voltage from the generator could be connected to a step-up transformer to increase the voltage and decrease the current, and so reduce energy loss in the transmission lines.

However, at the other end of the transmission line, the high voltage would be unsuitable, and possibly dangerous, for domestic appliances. So a step-down transformer is used to bring the voltage down to a safe level for home use.

In Victoria, electricity is generated at a variety of voltages. In Yallourn, the voltage is 20 000 V (20 kV). In Newport, the generating voltage is 24 000 V. From the various generators around Victoria, the voltage is stepped up to 500 kV to transmit the electrical energy over the long distances to Melbourne.

Because of the very high voltage, there is an increased risk of electrical discharge to the ground or the frame of the cable support, so tall towers are needed to hold the transmission cables high off the ground. Several porcelain discs are used to insulate the cables from the steel frame of the tower.

When the cables reach the outskirts of Melbourne, the high voltage is stepped down to 66 kV for distribution within the suburban area. In each suburb, the voltage is then further stepped down to 11 kV, either for delivery to yet another step-down transformer or to a neighbourhood power pole. There it is reduced to 230 V for connection to all the houses in the immediate neighbourhood.



Victoria's power system — a representation

The high-voltage transmission line feeds several outer suburban terminal stations, each of which passes the current to several zone substations. These substations each connect to hundreds of pole transformers, which then connect to hundreds of homes. As the distribution system spreads further and further down to the domestic consumer, the current in the transmission line at each stage gets less and less.

TABLE 8.1 Typical voltages in different sections of the transmission system

Ways to reduce resistance	Consequences
Major power tower or switchyard to terminal substation	220 kV, 330 kV or 500 kV
Terminal substation to zone substation	66 kV
Zone substation to pole-type transformer or underground transformer	22 kV
Pole-type transformer to house	230 V single phase, or 400 V for a three-phase supply

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This means that the cables in each section need to be designed to handle the current in that section in a cost-effective way, maximising energy transfer while minimising the cost of doing so. To minimise energy loss, the resistance of the cable needs to be made as small as possible.

PHYSICS IN FOCUS

Transmission lines

In transmission lines, the current actually flows through the outer surface of the line to a depth of about 1 mm. This is called the skin effect. It happens because the voltage is applied to the surface of the transmission line and the effect of the voltage decreases exponentially with distance from the surface.

Transmission lines are bare, multi-layered, concentrically stranded aluminium cables with a core of steel or reinforced aluminium for tensile strength. The advantages of wires in a bundle over a single conductor of the same area are lower resistance to AC currents, lower radio interference and audible noise, and better cooling.

The smaller the sag in a transmission line, the greater will be the tension in the line. As the transmission lines cool, they contract, producing greater tension. High winds also increase the tension. All these factors may need to be considered when designing a transmission system.

The cost of building a transmission line is very nearly proportional to the input voltage, and to the length of the line. The cost to transmit each unit of power is proportional to the length and inversely proportional to the square root of the power. That is, if the power to be transmitted is quadrupled, it can be transmitted twice as far for the same unit cost. It is therefore uneconomical to transmit power over a long distance unless a large quantity of power is involved.

The cost of constructing a line underground rather than above ground ranges from eight times as much as (at 69 kV) to 20 times as much (at 500 kV). Underground cables are usually stranded copper, insulated with layers of oil-soaked paper tape. Superconductive cables may make this a more economical proposition.

Basslink uses subsea cables to transmit high-voltage DC between Victoria and Tasmania.

TABLE 8.2 Ways to reduce resistance

Method	Effect
Make the wires fatter.	This increases the cost of the material in the wire and the cost of the pole to hold up the heavier wire.
Use a better conductor.	Metals differ in their electrical conductivity and in their economic value as a metal. Very good conductors such as gold and silver are too expensive to use as wires.

Imagine that 400 MW of power was available to be transmitted along a transmission line of 4.0 Ω. How would the power losses due to the resistance of the transmission line vary with the voltage across the transmission line? The following table shows some typical values.

TABLE 8.3 Transmission of 400 MW at different voltages

Transmission voltage	1000 kV	500 kV	220 kV	66 kV
Current $\left(I = \frac{P_{tot}}{V}\right)$	400 A	800 A	1800 A	6100 A
Power loss ($P_{loss} = I^2R$)	640 kW	2.6 MW	13 MW	150 MW
Power loss (%)	0.2%	0.6%	3.3%	37%

AS A MATTER OF FACT

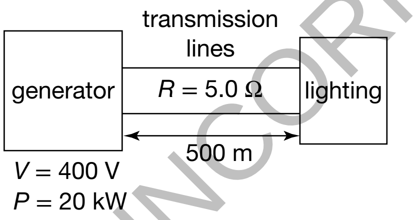
Electric power was first transmitted in 1882 by Thomas Edison in New York and by St George Lane-Fox in London, both using a DC system for street lighting. The transmission was at low voltage with considerable transmission power line losses, and so limited to short distances.

Later that decade, George Westinghouse purchased patents for AC generators. His company also improved the design of transformers, and developed an AC-based transmission system. In 1886 these new developments allowed power to be transmitted over a distance of a kilometre, stepping up the voltage to 3000 V and then stepping it down to 500 V.

In the 1800s there was much debate on the relative efficiency of the AC and DC transmission systems as well as on their environmental effects. However, the superiority of the AC system was soon realised. By 1898 there was a 30 000 V 120 km line, and by 1934 the voltage was up to 287 000 V over 430 km. During World War II German scientists developed 380 000 V and overcame the effect of electrical discharge by using double cables.

During the 1960s transmission voltages reached 765 000 V. Future voltages are expected to be at 1 000 000 V.

Sample problem 8.3



(a) A 20 kW, 400 V diesel generator supplies power for the 400 V lights on a film set at an outside location. The 500 m transmission cables have a resistance of 5.0 Ω.

(i) What is the current in the cables?
(ii) What is the voltage drop across the transmission cables?
(iii) What is the power loss in the cables as a percentage of the power supplied by the generator?
(iv) What is the voltage supplied to the lighting?

Solution: (i) Current in the cables = current coming from generator

For the generator: $P = 20\,000$ W, $V = 400$ V, $I = ?$

$$P = VI$$

$$20\,000\text{ W} = 400\text{ V} \times I$$

$$I = \frac{20\,000\text{ W}}{400\text{ V}}$$

$$= 50\text{ A}$$

Note: Using $V = IR$ with $V = 400$ V and $R = 5.0\ \Omega$ is incorrect because the 400 V is across both the cables *and* the load at the end.

(ii) For cables: $I = 50$ A, $R = 5.0\,\Omega$, $V = ?$

$$\begin{aligned} V &= IR \\ &= 50\text{ A} \times 5.0\,\Omega \\ &= 250\text{ V} \end{aligned}$$

(iii) For cables: $I = 50$ A, $R = 5.0\,\Omega$, $P_{\text{loss}} = ?$

$$\begin{aligned} P_{\text{loss}} &= I^2R \\ &= 50\text{ A} \times 50\text{ A} \times 5.0\,\Omega \\ &= 12\,500\text{ W} \end{aligned}$$

$$\text{As a percentage, }\%\,P_{\text{loss}} = \frac{12\,500\text{ W}}{20\,000\text{ W}} \times \frac{100}{1} = 62.5\%$$

Note: This answer could have been obtained by using $P = VI$, with $V = 250$ V from solution 2; however, there is a risk that 400 V may be used by mistake, so it is better to use I^2R.

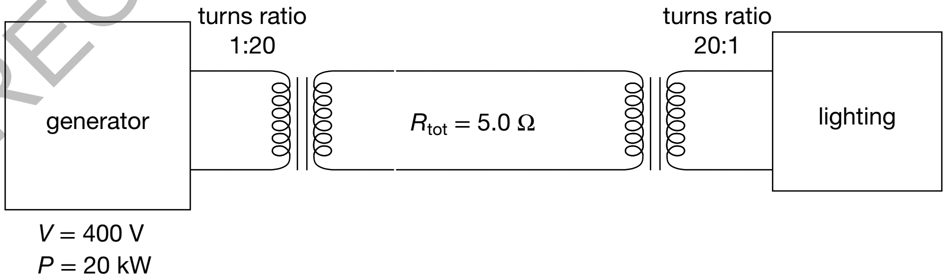
(iv) Generator voltage = sum of voltages in circuit

$V_{\text{gen}} = 400$ V, $V_{\text{cables}} = 250$ V, $V_{\text{load}} = ?$

$$\begin{aligned} 400\text{ V} &= 250\text{ V} + V_{\text{load}} \\ V_{\text{load}} &= 400\text{ V} - 250\text{ V} \\ &= 150\text{ V} \end{aligned}$$

At this distance the voltage drop across the cables is too much to leave sufficient voltage to operate the lights at their designated voltage. Given the noise of the generators, they cannot be moved closer. Therefore, step-up and step-down transformers with turns ratios of 20 are used to reduce the power loss in the cables and increase the voltage at the lights.

(b) Repeat the calculations in part (a), but this time increase the generator voltage by a factor of 20 and, prior to connection to the lights, reduce the voltage by a factor of 20.



(i) What is the current in the cables?
(ii) What is the voltage drop across the transmission cables?
(iii) What is the power loss in the cables as a percentage of the power supplied by the generator?
(iv) What is the voltage supplied to the lighting?

Solution: (i) Current in cables = current coming from step-up transformer

$$\begin{aligned} V_{\text{sec}} &= 20 \times 400\text{ V} \\ &= 8000\text{ V} \end{aligned}$$

For an ideal transformer: $P_{\text{prim}} = 20\,000$ W, $I_{\text{sec}} = ?$

$P_{\text{prim}} = P_{\text{sec}} = V_{\text{sec}}I_{\text{sec}}$

$20\,000\text{ W} = 8000\text{ V} \times I_{\text{sec}}$

$$\begin{aligned} I_{\text{sec}} &= \frac{20\ 000\,\text{W}}{8000\,\text{V}} \\ &= 2.5\ \text{A} \end{aligned}$$

(ii) For cables: $I = 2.5$ A, $R = 5.0\,\Omega$, $V = ?$

$$\begin{aligned} V &= IR \\ &= 2.5\,\text{A} \times 5.0\,\Omega \\ &= 12.5\,\text{V} \end{aligned}$$

(iii) For cables: $I = 2.5$ A, $R = 5.0\,\Omega$, $P_{\text{loss}} = ?$

$$\begin{aligned} P_{\text{loss}} &= I^2R \\ &= 2.5\,\text{A} \times 2.5\,\text{A} \times 5.0\,\Omega \\ &= 31.25\,\text{W} \end{aligned}$$

$$\text{As a percentage, } \%\ P_{\text{loss}} = \frac{31.25\,\text{W}}{20\ 000\,\text{W}} \times \frac{100}{1} = 0.16\%.$$

This is $\left(\frac{1}{20}\right)^2$ or $\frac{1}{400}$ of the original power loss! This is an impressive reduction.

(iv) Voltage supplied to step-down transformer = 8000 V − 12.5 V = 7988 V

Voltage supplied to lighting:

$$\begin{aligned} V_{\text{sec}} &= 7988\,\text{V} \times \frac{1}{20} \\ &= 400\,\text{V} \end{aligned}$$

Actually, the two-figure accuracy of the turns ratio means that the voltage 7988 V should be rounded to 8000 V.

Revision question 8.2

A remote community uses a 50 kW, 250 V generator to supply power to its hospital. The power is delivered by a 100-metre cable with total resistance of 0.20 Ω.

(a) Answer the questions in part (a) of sample problem 8.3 as they apply to this question.

(b) Transformers with a turns ratio of 10:1 are installed. Repeat (a) with this new ratio.

Using Ohm's Law wisely

The relationship $V = IR$ (Ohm's Law) is very useful. It can be applied in many situations in the one problem. This usefulness can lead to error if Ohm's Law is not applied wisely. The errors occur when students assume that having calculated a value for V, that value can be used every time $V = IR$ is used.

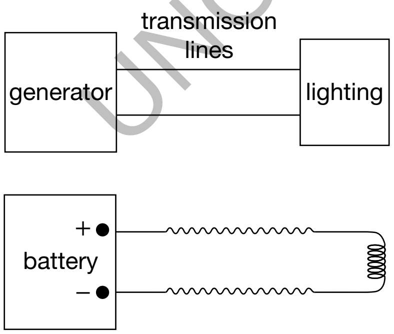
Rather, $V = IR$ should be remembered as:

Voltage across a section = current through the section × resistance of that section.

So, in transmission line problems, the voltage across the output of the generator is different from the voltage across the transmission lines, which is different, in turn, from the voltage across the load at the end of the lines.

A well-labelled diagram can help avoid this confusion. Imagine the generator as a battery and the two lines and the load as three separate resistors sharing the voltage from the battery.

In any electric circuit the total resistance determines how much current is drawn from the power supply. If there are transformers in the circuit, this statement is still true, but there are different currents and voltages on each side of the transformer.



Circuit diagram and battery circuit

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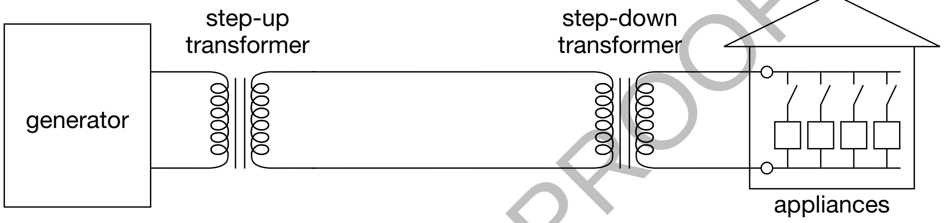
As more appliances are turned on, there is a larger secondary current, which causes a larger primary current to be drawn from the power supply. This means the secondary current drives the primary current. When all the appliances are turned off, there is no secondary current and, so, no primary current.

However, the primary voltage determines the secondary voltage through the ratio of turns in the transformer.

With more appliances turned on, the current in the transmission lines between the transformers increases. The increased voltage drop across these lines means that there will be slightly less voltage across the primary turns of the step-down transformer. This will result in a slight drop in the voltage for each of the appliances.



An electric circuit with step-up and step-down transformers

REMEMBER THIS

Electric power is normally discussed in terms of watts or megawatts — for example, when comparing electrical generators or deciding between vacuum cleaners. However, the generator supplies *energy*, the cleaner consumes *energy*, and it is ultimately we who pay for *energy*. The **power rating**, or wattage, of an electrical appliance indicates the rate at which it uses electricity. The longer it is on, the more energy is used and the more it costs. By definition:

1 watt = 1 joule per second, so
1 joule = 1 watt × 1 second, or 1 watt second.

As 1 watt second is equivalent to 1 joule, then

1000 watt seconds = 1000 J, or
1 kilowatt second = 1 kJ.

If a 1 kW heater was on for 1 s, it would use 1 kilowatt second or 1 kilojoule of electrical energy. If it was on for 60 seconds, it would use 60 kilowatt seconds or 60 kilojoules.

The common unit for energy supply and consumption in electricity is the kilowatt hour, which is the amount of energy consumed, for example, by a one-kilowatt heater for one hour. This unit is abbreviated to kWh (e.g. 60 kWh).

Conversion from kilowatt hour to joules:

$$\begin{aligned} 1\ \text{kWh} &= 60 \times 60\ \text{kilowatt seconds} \\ &= 3600\ \text{kilowatt seconds} \\ &= 3\,600\,000\ \text{watt seconds} \\ &= 3.6 \times 10^6\ \text{joules} \\ &= 3.6\ \text{megajoules.} \end{aligned}$$

The **power rating**, or wattage, of an electrical appliance indicates the rate at which it uses electrical energy.

Chapter review

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Summary

- A transformer is a device in which two multiple-turn coils are wound around an iron core. One coil, the primary coil, acts as an input; the other, the secondary coil, acts as an output.
- In a transformer, the iron core transfers the changing magnetic flux produced by an AC current in the primary coil to the secondary coil. The changing magnetic flux in the secondary coil induces an alternating voltage, producing an alternating current.
- The purpose of the transformer is to produce an output AC voltage that is different from the input AC voltage.
- A step-up transformer produces an output (secondary) voltage that is greater than the input (primary) voltage. A step-down transformer produces an output (secondary) voltage that is less than the input (primary) voltage.
- The relationship between the primary voltage and secondary voltage of a transformer is given by the equation:

$$\frac{V_{\text{prim}}}{V_{\text{sec}}} = \frac{N_{\text{prim}}}{N_{\text{sec}}}$$

- An ideal transformer does not lose energy. The power output of the secondary coil is equal to the power input of the primary coil. Thus

$$V_{\text{prim}} I_{\text{prim}} = V_{\text{sec}} I_{\text{sec}}.$$

- Real transformers lose energy in transferring electric power from the primary coil to the secondary coil. Some is lost in the wires that make up the coils. Some energy is lost due to induced currents (eddy currents) in the iron core.
- When AC electric power is transmitted over long distances, some energy is lost due to the resistance of the transmission lines. The rate at which energy is lost can be calculated using the formula $P = I^2R$.
- The power losses in long-distance transmission lines can be reduced by using step-up transformers to increase the transmission voltage, thereby reducing the transmission current. Step-down transformers are then used to reduce the voltage supplied to homes and industrial customers.

Questions

Transformers

1. An ideal transformer has 100 turns in the primary coil and 2000 turns in the secondary coil. If the primary coil was connected to 230 V AC, what would be the voltage across the secondary coil?
2. A transformer has 300 turns in the primary coil and six turns in the secondary coil.
   (a) If 230 V AC is connected to the primary coil, what will be the voltage across the secondary coil?
   (b) If the secondary voltage is 9.0 V AC, what is the voltage across the primary coil?
3. Christmas tree lights need a transformer to convert the 230 V AC to 12 V AC.
   (a) If there are 50 coils on the 12 V secondary coil, how many turns are there in the primary coil?
   (b) If there are 20 globes connected in parallel to the secondary coil, each of 12 V and 5 W, what is the current in the secondary coil?
   (c) What is the current in the primary coil, assuming the transformer is ideal?
4. Explain why a transformer does not work with a constant DC input voltage.
5. Why is the core of transformers made of an alloy of iron that is easy to magnetise?
6. A transformer is used to change 10 000 V to 230 V. There are 2000 turns in the primary coil.
   (a) What type of transformer is this?
   (b) How many turns are there in the secondary coil?
7. An ideal transformer has 400 turns in the primary coil and 900 turns in the secondary coil. The primary voltage is 60 V and the current in the secondary coil is 0.30 A.
   (a) What is the voltage across the secondary turns?
   (b) What is the power delivered by the secondary coils?
   (c) What is the current in the primary coil?

Transmission lines

8. An isolated film set uses a 50 kW generator to produce electricity for lighting and other purposes at 250 V RMS. The generator is connected to lights about 100 m away by transmission cables with a combined resistance of 0.3 Ω.
   (a) When the generator is operating at full capacity, what current does it supply?
   (b) What is the power loss in the transmission cables?
   (c) What is the total drop in voltage across the two cables connected by the generator?
   (d) What is the voltage supplied to the lights?
   (e) Two transformers with a turns ratio of 20 are used to first step up the voltage from the generator to the cables, and then to step it down from the cables to the lights. Using this new information, answer (b) to (d) above again.

9. The appliances in a house would, if all turned on and connected to a power supply of 230 V, draw a current of 40 A.
  (a) What is the effective resistance of the appliances in the house, when they are all turned on?

However, the house is some distance from the power lines and the connecting cables have a resistance of 0.20 Ω.
  (b) What is the total resistance of the circuit connected to the power lines?
  (c) If the voltage at the power lines is 230 V AC, what is the voltage at the house?
  (d) A 20 kW workshop which operates off the 230 V supply is installed in the garage in parallel to the house. Answer parts (b) and (c) again for the new situation.

  The owners now decide to install a step-up transformer and a step-down transformer, each with a turns ratio of 10:1, at either end of the transmission lines.
  (e) If the system draws 120 A from the grid at 230 V, will the voltage at the house and the garage be within 1% of 230 V for the appliances to work properly?
  (f) At night the workshop is turned off. Will the voltage at the house increase, decrease or remain unchanged? Give reasons.

10. A generator at a power station produces 220 MW at 23 kV. The voltage is then stepped up to 330 kV. The power passes along transmission lines with a total resistance of 0.40 Ω.
  (a) What is the current in the transmission lines?
  (b) What is the power loss in transmission lines?
  (c) What is the voltage drop across them?
  (d) What voltage and power is available to the step-down transformer located at the end of the lines ?

11. The maximum electrical power the generator at a power station can deliver is 500 MW at a voltage of 40 kV. This power is to supply the electricity needs of a distant city. Transmission lines connecting the station to the city have a total resistance of 0.8 Ω. At the city, the transmission lines are connected to a series of step-down transformers that reduce the voltage to 230 V. The city wants a two-step evaluation of the transmission system.
  (a) What percentage of the power delivered by the power station is lost in the transmission lines?

The power loss can be reduced by stepping up the voltage at the generator with a transformer. At the substations on the city's outskirts, the voltage is stepped down. The voltage could be stepped up to 400 kV with a transformer with a turns ratio of 10:1. The same transmission lines could be used, but they would need to be raised higher off the ground and be better insulated at each pole.
  (b) What would be the effect on the power loss in the transmission lines?