CHAPTER 8

Transformers

Transformers allow generated voltage to be either increased or decreased before it is used

Introduction

Transformers are devices that are able to change the size of input voltage via electromagnetic induction. They are found everywhere! They can take the form of large rectangular boxes that are found buried underground or hanging on telegraph poles. Smaller versions are found at the end of power cords for various types of chargers and electronic devices at home. Transformers have important impacts on both the society and the environment, and these will be discussed in this chapter.

8.1 Transformers: What are they?

■ *Describe the purpose of transformers in electrical circuits*

Definition

Transformers are devices that increase or decrease the size of the AC voltage as it passes through them.

The simplest transformer consists of:

- A **primary coil** where the AC voltage is fed in.
- A **secondary coil** as the output that will be connected to a load. The secondary coil will have different turns of coil to the primary coil depending on whether it increases or decreases the voltage.
- Both the primary coil and secondary coil are wound around a **soft iron core**.

NOTE: The 'soft iron' in this context refers to pure irons. Unlike steel, pure irons are generally quite soft.

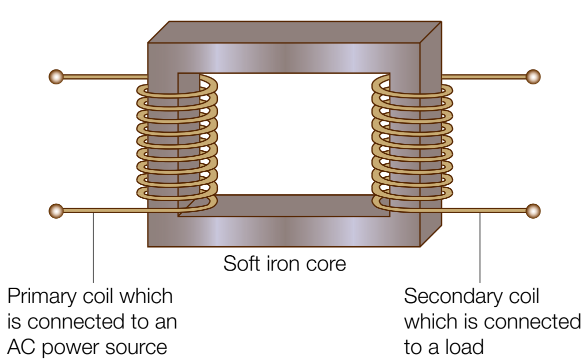

Figure 8.1 A transformer

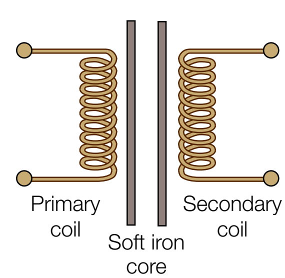

Figure 8.2 Transformer circuit symbol

Principle of operation

How does a transformer change the voltage of the AC power input?

When the AC power is fed into the primary coil of the transformer, the changing current of the AC produces its own changing magnetic flux. The magnetic flux is linked to the secondary coil via the soft iron core. In the secondary coil, this changing magnetic flux will induce an EMF as the output.

Since the size of the magnetic flux developed in the primary coil depends on the number of turns of the primary coil, and the EMF induced in the secondary coil also depends on the number of turns of the secondary coil, logically, by varying the number of turns of coil, the voltage induced in the secondary coil can be either larger or smaller than that in the primary coil.

NOTE: Because a changing magnetic flux is essential in electromagnetic induction, transformers *do not work for DC* due to the constancy in its current and the associated magnetic flux.

The role of the soft iron core in transformers

Besides acting as a support frame on which the coils can be wound, the soft iron core in transformers has two additional very important roles:

1. The soft iron acts as a medium through which magnetic flux can flow.

   ANALOGY: Just as sound travels best in dense solids, magnetic flux travels best in (soft) iron.

   Therefore, the soft iron core is responsible for linking the magnetic flux from the primary coil to the secondary coil.
2. More importantly, soft iron is used as the core in order to amplify or intensify the magnetic flux, so that the mutual induction process becomes more efficient.

The way soft iron can magnify magnetic flux is by aligning its randomly orientated domains with the external magnetic field, becoming a temporary ferromagnet that produces its own magnetic flux, which is added to the existing magnetic flux. This idea is illustrated in Figure 8.3 (a) and (b).

NOTE: Domains are the smallest units in a material that possess a net magnetic field. Each domain contains billions of atoms. The magnetic field of the domains is produced by the moving electrons of the atoms.

NOTE: Similarly, for the purpose of magnifying magnetic flux, coils in motors and generators are wound on soft iron cores.

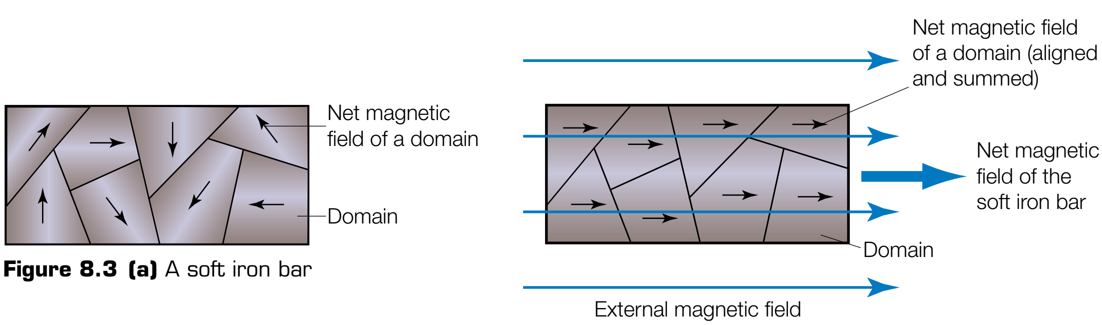

Figure 8.3 (a) A soft iron bar

Figure 8.3 (b) A soft iron bar within an external magnetic field

Energy lost in transformers

SECONDARY SOURCE INVESTIGATION

PFAs

H3

PHYSICS SKILLS

H13.1A, B, C, D
H14.1G, H

■ *Gather, analyse and use available evidence to discuss how difficulties of heating caused by eddy currents in transformers may be overcome*

If a transformer is 100% energy efficient, then the energy of the AC power input into the primary coil should equal to the power output of the secondary coil.

However, in reality, transformers are not perfectly efficient. A portion of the input energy is lost during the process of mutual induction. The energy loss is mainly in the form of heat, which is dissipated by both the primary and secondary coils, but, more extensively, by the soft iron core.

The reason for the heat dissipation by the soft iron core is as follows: just like the secondary coil, the soft iron core is also subject to the changing magnetic flux produced by the current in the primary coil. Being a solid conductor, there will be eddy currents generated in it. The circulation of eddy currents in the core then generates heat—similar to how induction cooktops use eddy currents to heat food—which is then dissipated to the surroundings.

Soft iron core showing the lamination

How can the heat lost by the core be minimised?

To minimise the heat dissipation by the soft iron core, the core is laminated.

Lamination means the core is constructed using stacks of thin iron sheets, each coated with insulation materials so that it is electrically insulated from the neighbour iron sheets (see Fig. 8.4).

Lamination effectively increases the resistance of the core to the flow of eddy currents, therefore restricting the circulation of large eddy currents. This leads to a decrease in the heat dissipation by the core, and increases the overall energy efficiency of the transformer.

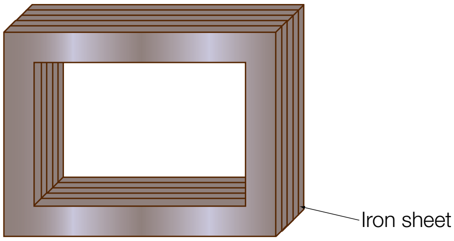

Figure 8.4 Lamination

8.2 Types of transformers

■ *Compare step-up and step-down transformers*

Generally, there are two types of transformers, classified based on whether they increase or decrease the input voltage.

Step-up transformers

For step-up transformers, the voltage output from the secondary coil is larger than the voltage input into the primary coil. (Hence 'step up'.) The secondary coil has more turns than the primary coil.

Step-down transformers

For step-down transformers, the voltage output from the secondary coil is smaller than the voltage input into the primary coil. (Hence 'step down'.) The secondary coil has fewer turns than the primary coil.

8.3 Calculations for transformers

- ***Identify the relationship between the ratio of the number of turns in the primary and secondary coils and the ratio of primary to secondary voltage***
- ***Explain why voltage transformations are related to conservation of energy***

- ***Solve problems and analyse information about transformers using***
  $$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

Calculating the voltage change

To quantitatively calculate the voltage change for a given transformer, we need the formula:

$$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

Where:

V_p = voltage input into the primary coil, measured in V

V_s = voltage output from the secondary coil, measured in V

n_p = number of turns of the primary coil

n_s = number of turns of the secondary coil

NOTE: the 'voltage' in this section refers to AC voltages.

Example 1

A transformer has a primary coil of 2500 turns and a secondary coil of 500 turns.

(a) Classify this transformer.

(b) If the input voltage of the primary coil is 240 V, what will the voltage output of the secondary coil be?

Solution

(a) This is a step-down transformer, as there are fewer turns of coil in the secondary than the primary.

(b) $\dfrac{V_p}{V_s} = \dfrac{n_p}{n_s}$

$$\frac{240}{V_s} = \frac{2500}{500}$$

$$V_s = 48 \text{ V}$$

Example 2

A discman will only function if it is fed a voltage of 4.5 V. The common household voltage is 240 V. What will be the required turn ratio between the primary and secondary coil if a transformer is to be used?

Solution

$$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

$$\frac{240}{4.5} = \frac{n_p}{n_s}$$

$$\therefore \frac{n_p}{n_s} = \frac{160}{3}$$

∴ the turn ratio between the primary coil and the secondary coil should be 160:3.

Calculating the power for transformers

Recall that power in electricity is the product of voltage and current. Or mathematically:

$$P = IV$$

Where:

P = power, measured in W

I = current, measure in A

V = voltage, measured in V

NOTE: For a perfectly energy efficient transformer, the power input should be equal to the power output. This is known as the law of conservation of energy.

Example 1

For a transformer, the voltage and current input into the primary coil is 240 V and 2.00 A respectively.

(a) Calculate the power input of the transformer.

(b) Calculate the power output if the transformer is 100% energy efficient.

Solution

(a) $P_p = V_pI_p$

$V_p = 240$ V

$I_p = 2.00$ A

$\therefore P_p = 240 \times 2.00 = 480$ W

(b) 480 W. If the transformer is 100% energy efficient, then the power input should equal the power output as a consequence of the law of conservation of energy.

Example 2

The transformer of a battery recharger has a voltage and current input of 240 V and 3.00 A respectively. If the transformer dissipates 30% of the input energy, what will be the power output from the secondary coil?

Solution

$$P_p = V_pI_p$$
$$= 240 \times 3 = 720 \text{ W}$$

Since the primary coil loses 30% of its energy, therefore the power in the secondary (P_s) will be 70% of that of the Primary (P_P)

$$\therefore P_s = 70\% \times P_p = 0.7 \times 720 = 504 \text{ W}$$

Calculating the current change

In these calculations, for convenience, we will assume the transformers are 100% energy efficient. Therefore:

$$P_p = P_s$$
$$P = VI$$
$$V_pI_p = V_sI_s$$
$$\frac{V_p}{V_s} = \frac{I_s}{I_p}$$

Combined with the equation on page 152, we have:

$$\frac{n_p}{n_s} = \frac{V_p}{V_s} = \frac{I_s}{I_p}$$

Where:

n_p = the number of turns of the primary coil

n_s = the number of turns of the secondary coil

V_p = voltage input into the primary coil, measured in V

V_s = voltage output from the secondary coil, measured in V

I_p = current input into the primary coil, measured in A

I_s = current output from the secondary coil, measured in A

Example 1

A transformer at a power plant has a primary coil with 1000 turns. The voltage input into the primary is 23 kV and is stepped up to 330 kV. Assume this transformer is 100% efficient.

(a) Find the number of turns of the secondary coil.

(b) If the power input of the primary coil is 230 MW, calculate the current in the secondary coil and compare it to that of the primary.

Solution

(a) $$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

$$\frac{23 \times 10^3}{330 \times 10^3} = \frac{1000}{n_s}$$

$$\therefore\ n_s \approx 1.4 \times 10^4 \text{ turns}$$

(b) Since the power input is 230 MW, the power in the secondary must also be 230 MW if the transformer is 100% efficient, therefore:

$$P_s = V_s I_s$$

$$P_s = 230000000 \text{ W}$$

$$V_s = 330000 \text{ V}$$

$$I_s \approx 697 \text{ A}$$

NOTE: Therefore, as the voltage is stepped up, the size of the current in the coil is reduced, and vice versa.

Example 2

An industrial transformer has a primary coil with 6000 turns. The voltage of the primary coil is 415 V, and the voltage of secondary is 12 V. Assume the transformer is 100% energy efficient.

(a) How many turns are there in the secondary coil?

(b) If the current in the primary coil is 12 A, calculate the current in the secondary coil.

(c) Explain why the thickness of the wires in secondary coil is much larger than that in the primary coil.

Solution

(a) $$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

$$\frac{415}{12} = \frac{6000}{n_s}$$

$$\therefore\ n_s \approx 174 \text{ turns}$$

(b) $\frac{I_s}{I_p} = \frac{n_p}{n_s}$

$\frac{I_s}{12} = \frac{6000}{174}$

$I_s \approx 415$ A

(c) A thicker wire in the secondary coil is needed to accommodate the large current, as a thin wire would overheat.

8.4 Voltage changes during the transmission from power plants to consumers

■ *Explain the role of transformers in electricity sub-stations*

At a power plant, various energy transformations are used to produce electricity. For example, burning of fossil fuels converts water to steam, which is then used to turn the turbines of an (AC) electric generator. Electricity is generated based on the principle of electromagnetic induction as discussed in Chapter 6.

The voltage change during the transmission from the power plant to consumers can be described using a flow chart:

Electricity is usually generated by a three-phase AC generator; generally the voltage generated is as big as 23 000 V and current output from each set of the coil is almost 10000 A.

↓

For long distance transmissions, the electricity is then fed into a step-up transformer that increases the voltage to 330 000 V and correspondingly decreases the size of the current. (See example on page 155.) This is done to increase the efficiency of the transmission of the electricity as explained below.

↓

After this electricity has been transmitted over a long distance, the voltage is stepped down at different regional sub-stations, mainly for safety reasons. Correspondingly, the current increases.

↓

Eventually, the voltage is stepped down to 240 V at the local telegraph pole transformers for domestic uses; industries may use slightly higher voltages.

A switching yard at a regional substation

A transformer at a regional substation

A transformer mounted on power poles

SR

Electricity transmission infrastructure of eastern Australia

The role of transformers for long-distance transmissions

SECONDARY SOURCE INVESTIGATION

PFAs

H3

PHYSICS SKILLS

H13.1A, B, C

■ ***Gather and analyse secondary information to discuss the need for transformers in the transfer of electrical energy from a power station to its point of use***

Why is there a need to step up the voltage for long-distance transmissions?

As a current passes through conductors, energy, mainly in the form of heat, is lost to the surroundings. The amount of energy lost is related to the **size of the current** as well as the **resistance** of the conductor, and can be described by the formula $P = I^2R$—where P is the energy lost in J, I is the size of the current in amperes and R is the total resistance of the conductor in Ω (ohms). Since resistance is proportional to the length of the conductor, a long transmission wire will inevitably have a high resistance; consequently there will be a large amount of heat dissipated when electricity passes through it.

Increasing the voltage of the electricity for transmission effectively decreases the size of the current running through the wire without changing the power transmitted. Since the energy lost is *proportional to the square of the size of the current*, having a smaller current decreases the energy lost during transmission dramatically, thus making the transmission much more efficient.

Making wires from materials that have very low electrical resistance, such as aluminium or copper, will also reduce the energy loss during transmission.

NOTE: The fact that transformers do not work for DC means there is no easy way of stepping up a DC voltage for transmission. Large currents would run through transmission wires, which would lead to enormous amounts of energy loss in the form of heat. This makes DC transmission extremely inefficient, which is the main reason why DC is not used on a large scale today. This is also why Westinghouse's AC system became more widespread than Edison's DC system.

8.5 The need for transformers in household appliances

An example of a transformer used at home

■ *Discuss why some electrical appliances in the home that are connected to the mains domestic power supply use a transformer*

Large power plants, regional sub-stations and many household appliances have transformers. Many household appliances function at voltages other than the standard domestic voltage of 240 V:

- *Some appliances require step-up transformers*: For instance, a TV requires thousands of volts for its operation in the cathode ray tube.
- *Some appliances require step-down transformers*: For instance, scanners, toys and computers require lower voltage for their correct operation as well as for safety reasons. Also, some electric ovens and cooktops need to step down the input voltage in order to increase the size of the current, which effectively increases the heating effect of such devices.

8.6 The impact of the invention of transformers

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'Discuss'

■ *Discuss the impact of the development of transformers on society*

Once again, you need to come up with your own opinions and support them by examples and evidence based on your own research. Arguments must be logical and succinct.

Here are some ideas for the impact of the development of transformers.

- *A shift from DC usage to AC usage*: As described in Chapter 7, Edison's DC system dominated the electricity market during the early years. However, this was revolutionarily shifted to Westinghouse's AC system, mainly due to the invention of transformers, which allowed AC to be easily stepped up or down for efficient transmissions.
- *The efficiency in transmission of electricity*: The power loss during transmission is dramatically reduced as a consequence of the development of transformers. This means electricity transmission becomes more economical, thus reducing the price of electricity. Less energy loss also means we are indirectly saving our energy expenses thus decreasing our consumption of fossil fuels. Moreover, fewer fossil fuels will need to be burnt to provide us with the same amount of electricity, which is more environmentally friendly.
- *Allows distant location of power stations*: The development of transformers led to efficient transmission, which means we can afford to put large power plants a long distance away from the site of electricity consumption. This allows the generation of electricity to be concentrated at one place, as well as allowing these power plants to move away from metropolitan

Power transmission lines

areas, which decreases the level of pollution or other types of hazards in metropolitan areas. Imagine if you had a huge power plant right next your house!

- *Allows the development of appliances which run at different voltages*: Only with the development of transformers are appliances such as TVs, scanners and computers, which run at voltages other than 240 V, made possible.

Producing secondary voltage

Perform an investigation to model the structure of a transformer to demonstrate how secondary voltage is produced

In this investigation, we model the structure and demonstrate the operation of a transformer.

Procedure

1. Wind a primary coil around a soft iron bar, carefully counting the number of turns.
2. Wind a secondary coil—for better linkage of magnetic flux, the secondary coil can be wound on top of the primary coil—and also note the number of turns.
3. Connect the primary coil to an AC power source from a power pack with known voltages.
4. Measure the AC voltage outputs from the secondary coil using a cathode ray oscilloscope. **Caution:** Ensure the secondary coil has fewer turns than the primary coil.
5. Compare the measured values to the theoretically calculated values based on the turn ratios.
6. Compare the structure of your model transformer with that of an induction coil.

Some questions for you to think about

- Why do the measured voltages differ from the theoretically calculated voltages based on the turn ratios?
- What will be the effect of removing the soft iron bar?
- What will be the effect of winding the secondary coil on a different soft iron bar? What will happen to the secondary voltage as you move the primary and secondary coils further and further apart?

FIRST-HAND INVESTIGATION

PHYSICS SKILLS

H12.1A, B, D
H12.2A
H12.3A
H14.1A, B, C, D

TR

Risk assessment matrix

CHAPTER REVISION QUESTIONS

1. (a) Explain why transformers do not work for DC.
   (b) Name one device that can be used to change the voltage for a DC source.
2. For the following transformers, find:
   (a) the secondary coil voltage, given that the primary coil is 50 turns, the secondary coil is 75 turns and the voltage of the primary coil is 11 V
   (b) the primary coil voltage, given that the primary coil is 2000 turns, the secondary coil is 6500 turns and the voltage of the secondary coil is 66 kV
   (c) the secondary current, given that the primary coil is 825 turns, the secondary coil is 175 turns and the current in the primary coil is 12 mA

3. A household step-down transformer has 500 turns in its primary coil.
   (a) Define the term 'step down'.
   (b) Assume this transformer is perfectly energy efficient. If the voltage is reduced from 240 to 12 V by the transformer, how many turns of coil are there in the secondary?
   (c) Use the information in part (b), but now assume this transformer is only 80% energy efficient. If 2.0 A is fed into the primary coil, what is the size of current flowing through the secondary coil?
   (d) Account for why transformers are often not 100% energy efficient.

4. Describe in detail how electricity is transmitted from a power station to households. In your answer, you should include the changes in voltage involved.

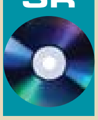
5. Name two electric appliances that require transformers for their function.

6. Evaluate the impact of the development of transformers on society and on the environment.

7. In many school experiments conducted with transformers, a primary coil is wound on a steel rod, and the secondary coil is wound over the primary coil.
   (a) Justify why the secondary coil is wound over the primary coil.
   (b) What is the role of the steel rod?
   Both the primary coil and the secondary coil now have a voltmeter and an ammeter connected. Readings are recorded in the table below:

Primary voltage (V)	Secondary voltage (V)	Primary current (A)	Secondary current (A)
2.0	4.1	1.0	0.3
3.9	5.9	2.2	0.8
5.8	12.0	3.4	1.3
8.1	16.0	4.0	1.7
10.0	20.3	5.1	2.4

   (c) If the primary coil has exactly 50 turns, how many turns would the secondary coil have? Show all working.
   (d) Is the transformer perfectly efficient? Comment.
   (e) Suggest one thing that can be done (at least in theory) to make this transformer more efficient.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Answers to chapter revision questions