Cambridge IGCSE · Physics 0625 · Notes

Electromagnetic effects

Read online at **pastopic.com/cambridge/physics-0625/notes/electromagnetic-effects**

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Read first: **Simple phenomena of magnetism**, Electrical quantities

What you need to know

This topic links electricity and magnetism both ways: a current makes a magnetic field, a magnetic field pushes on a current, and a changing magnetic field makes a voltage. It is the physics behind motors, generators, relays, loudspeakers and transformers. It uses magnetic fields and poles from the magnetism topic, and $P = IV$ and a.c. from electrical quantities. The parts marked **Extended only** are tested on Papers 2 and 4 only. By the end of it you should be able to:

Electromagnetic induction

1. **Know that an e.m.f. (a voltage) is induced in a conductor** when it moves across a magnetic field, or when the magnetic field linking it changes.
2. **Describe an experiment that shows electromagnetic induction.**
3. **State the factors that affect the size of an induced e.m.f.**
4. **Extended only:** know that the direction of an induced e.m.f. opposes the change that causes it.
5. **Extended only:** state and use the relative directions of force, field and induced current.

The a.c. generator

6. **Extended only:** describe a simple a.c. generator (a rotating coil, or a rotating magnet), and the use of slip rings and brushes where they are needed.
7. **Extended only:** sketch and interpret graphs of e.m.f. against time for a simple a.c. generator, and link the position of the coil to the peaks, troughs and zeros of the e.m.f.

The magnetic effect of a current

8. **Describe the pattern and direction of the magnetic field** due to a current in a straight wire and in a solenoid.
9. **Describe an experiment to find that pattern and direction.**
10. **Describe how relays and loudspeakers use the magnetic effect of a current**, with examples of where they are used.
11. **Extended only:** state how the strength of the field changes around a straight wire and a solenoid.
12. **Extended only:** describe what happens to the field when the size or the direction of the current changes.

The force on a current-carrying conductor

13. **Describe an experiment showing that a force acts on a current-carrying conductor in a magnetic field**, and what happens when the current or the field is reversed.
14. **Extended only:** recall and use the relative directions of force, field and current.
15. **Extended only:** find the direction of the force on a beam of charged particles in a magnetic field.

The d.c. motor

16. **Know that a current-carrying coil in a magnetic field can experience a turning effect**, and that the turning effect is bigger with more turns on the coil, a bigger current or a stronger magnetic field.
17. **Extended only:** describe how an electric motor works, including what the split-ring commutator and the brushes do.

The transformer

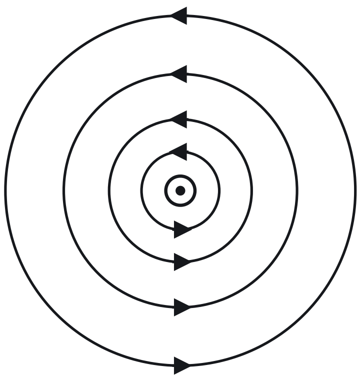
18. **Describe the construction of a simple transformer with a soft-iron core.**
19. **Use the words primary, secondary, step-up and step-down.**
20. **Recall and use $\frac{V_p}{V_s} = \frac{N_p}{N_s}$.**
21. **Describe how transformers are used in high-voltage transmission of electricity**, and **state the advantages of transmitting at a high voltage.**
22. **Extended only:** explain how a simple iron-cored transformer works.
23. **Extended only:** recall and use $I_p V_p = I_s V_s$ for a transformer that is 100% efficient.
24. **Extended only:** recall and use $P = I^2 R$ to explain why less power is lost in the cables when the voltage is higher.

Understand it

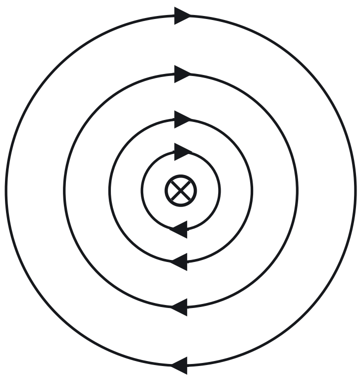
The magnetic field of a straight wire

A current in a wire makes a **magnetic field** around it: a region where a magnetic pole feels a force. For a long straight wire the field lines are **circles centred on the wire**, in planes at right angles to it.

The direction comes from the **right-hand grip rule**: grip the wire with your right hand, thumb pointing along the (conventional) current. Your fingers curl the way the field lines go. Seen from above, a current **coming out of the page** gives field lines going **anticlockwise**; a current **into the page** gives **clockwise** lines. On a diagram, a dot in a circle means current out of the page and a cross means into it.



current out of the page
field anticlockwise



current into the page
field clockwise

Extended only: the field is **strongest close to the wire** and gets **weaker further away**, so the circles are drawn further and further apart. A **bigger current** gives a **stronger field** (circles drawn closer together); **reversing the current reverses the field direction**, but the pattern stays the same.

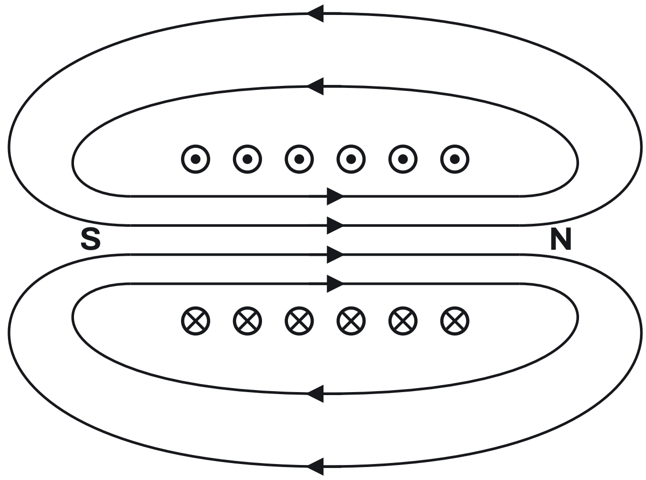
The experiment. Pass a vertical wire through a hole in a horizontal piece of card and connect it to a supply that gives a large current. Sprinkle **iron filings** on the card and tap it gently: they line up in circles round the wire (this shows the pattern). Then place small **plotting compasses** on the card: each needle lines up along a circle, and its N end points the way the field goes (this shows the direction). Reverse the current and every compass needle turns round. Switch the current off and the compasses all point north again, along the Earth's field.

The magnetic field of a solenoid

A **solenoid** is a long coil of wire. The fields of all its turns add up, so it has a field **like a bar magnet's**:

- **inside**, the lines are **straight, parallel and evenly spaced**: the field is strong and nearly the same everywhere (uniform);
- **outside**, the lines curve round from one end to the other, just like the lines round a bar magnet, and they never cross;
- one end acts as an **N pole** (field lines come out) and the other as an **S pole** (field lines go in).

To find which end is N, look at the end: if the current goes round it **anticlockwise**, that end is **N**; if **clockwise**, it is **S**. (Or grip the solenoid with your right hand, fingers curled along the current: your thumb points to the N end.)



top row: current out of the page · bottom row: current into the page

Extended only: the field is **strongest inside** the solenoid, where the lines are closest; it gets weaker beyond the ends and is weak outside, where the lines spread out. A **bigger current** (or more turns) gives a stronger field; **reversing the current** swaps the N and S ends. The same compass and iron-filings experiment works: thread the coil through a card, or place plotting compasses round it.

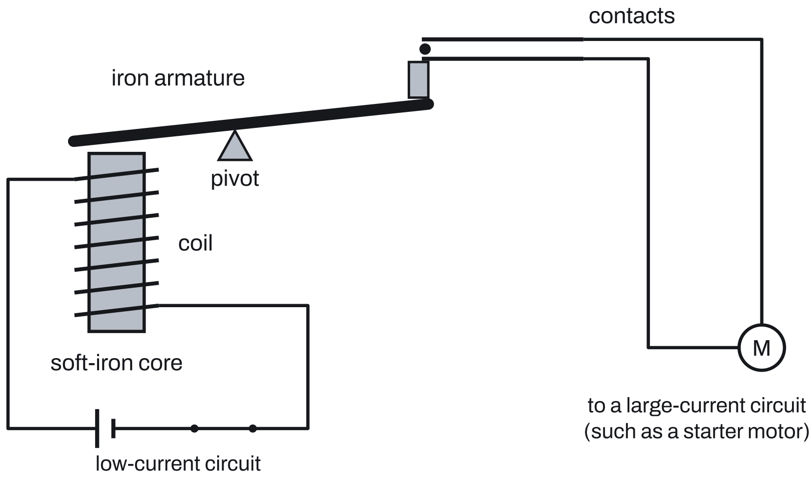
Electromagnets, relays, bells and loudspeakers

Put a **soft-iron core** inside a solenoid and you have an **electromagnet**: a much stronger magnet that can be switched on and off. Soft iron is used because it **loses its magnetism as soon as the current stops**; steel would stay magnetised. Any device that uses the magnetic effect of a current contains a coil: relays, bells, loudspeakers, motors, electromagnets and trip switches do; heaters, lamps, thermistors and potential dividers do not.

A relay is a switch worked by an electromagnet. A **small current** in one circuit switches on a **large current** in a second circuit:

1. a small current flows in the coil, so the coil and its soft-iron core become a magnet;
2. the core **attracts** the iron armature, which **pivots**;
3. the other end of the armature pushes the **contacts** together, closing the second circuit;
4. when the small current is switched off, the core loses its magnetism and a spring pulls the armature back, so the contacts open.

Relays let a small, safe current (from a low-voltage switch, a sensor or a control circuit) switch a large current or a mains voltage, for example a car's **starter motor**, a motor in a factory, or street lights switched by a light sensor.



An electric bell works the same way but switches **itself** off and on. Closing the switch sends a current through the solenoid, which becomes a magnet and **attracts the soft-iron arm**, so the striker hits the bell. But moving the arm **separates the contacts**, which **breaks the circuit**: there is no current, the solenoid stops being a magnet, and the **springy metal** pulls the arm back. That closes the contacts again, and the cycle repeats many times a second while the switch is held.

A loudspeaker has a coil fixed to a paper or plastic **cone**, sitting in the field of a **permanent magnet**. An alternating current from an amplifier flows in the coil. Because the current keeps changing direction, the **force on the coil** keeps changing direction too, so the coil and cone **vibrate** at the frequency of the current and push the air to and fro: sound. A bigger current gives a bigger force, bigger vibrations and a louder sound.

The force on a current in a magnetic field

A wire carrying a current across a magnetic field feels a **force**. The field of the current and the field of the magnet push on each other.

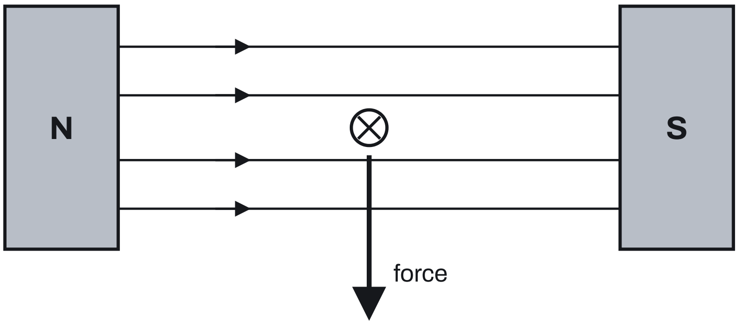
The experiment. Place a short straight wire (or a light metal rod resting on two metal rails) between the poles of a U-shaped magnet, at right angles to the field, and connect it to a supply. When the current flows, the wire jumps or rolls sideways. Then:

- **reverse the current**: the wire moves the **opposite** way;
- **reverse the field** (turn the magnet round): the wire moves the **opposite** way;
- reverse **both**: the force is back in the **original** direction;
- a **bigger current** or a **stronger magnet** gives a bigger force; a wire lying **along** the field lines feels **no** force.

Extended only: the left-hand rule. Hold your left hand with the thumb, first finger and second finger all at right angles to each other.

- **F**irst finger: **F**ield (from N to S).
- Se**c**ond finger: **c**urrent (conventional current, from + to −).
- Thu**m**b: the force, and so the **m**otion.

The force is at right angles to **both** the field and the current.



field: N to S (left to right) · current: into the page · force: down

Extended only: beams of charged particles. A beam of charged particles is a current, so the same rule works. For a beam of **positive** particles, the current is in the direction they move. For a beam of **electrons**, the current is in the **opposite** direction to their motion. The force is always at right angles to the motion, so a beam bends into a curve (a circle, if it stays in the field). Electrons and positive particles moving the same way are pushed in opposite directions.

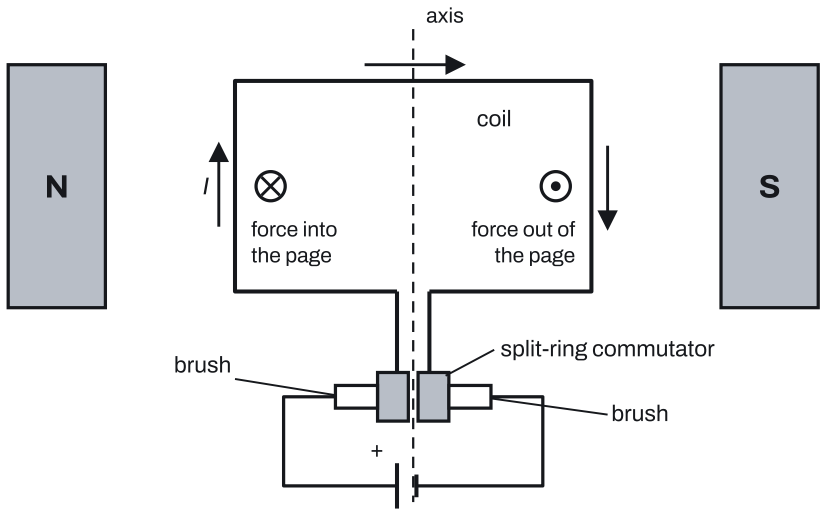
The d.c. motor

Put a rectangular **coil** in a magnetic field and pass a current through it. The two sides of the coil that are at right angles to the field carry current in **opposite directions**, so the forces on them are in **opposite directions**: one side is pushed up and the other down. That gives a **turning effect**, so the coil rotates about its axle.

The turning effect is **bigger** with:

- **more turns** on the coil;
- a **bigger current**;
- a **stronger magnet**.

Reversing the current, or swapping the magnets round, makes the motor turn the other way.



Here ⊗ and ⊙ show the force on each side, not the current.

Extended only: the split-ring commutator and brushes. The ends of the coil are joined to a **split ring**: a ring cut into two halves, which turns with the coil. Two **brushes** (usually carbon) press against it and connect it to the supply.

- The turning effect is **largest** when the plane of the coil is **parallel** to the field, and **zero** when the coil is **perpendicular** to the field (the forces then pull straight outwards, along the coil, not round it).
- As the coil passes that perpendicular position, the gaps in the split ring pass the brushes, and each half-ring swaps to the other brush. So the **current in the coil reverses every half turn**.
- The side of the coil now next to the N pole always has the current in the same direction as the side that was there before, so the force pushes it the **same** way: the coil keeps turning in **one direction**. Without the commutator, the forces would push it back after half a turn and it would just rock to and fro.
- The coil's **momentum** carries it through the position where the turning effect is zero.
- The **brushes** press on the split ring as it turns, keeping a sliding contact between the fixed supply and the turning coil.

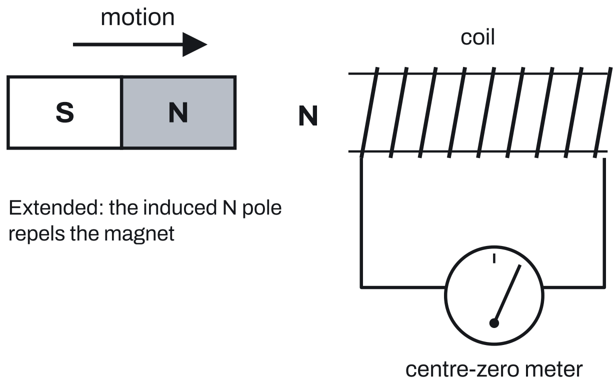
Electromagnetic induction

Run the motor idea backwards: **move** a wire across a magnetic field and a voltage appears across its ends. This is **electromagnetic induction**, and the voltage is an **induced e.m.f.** An e.m.f. is induced when:

- a conductor **moves across** (cuts) magnetic field lines, or
- the **magnetic field linking** a conductor or coil **changes** (a magnet moves near it, or the current in a nearby coil is switched on, off or changed).

If the conductor is part of a **complete circuit**, the induced e.m.f. drives an **induced current**. What matters is **relative movement** or a **changing field**: a wire held still in a steady field, or a wire moving **along** the field lines, has no e.m.f. induced in it, and neither does a magnet and coil that move together.

The experiment. Connect a coil to a **sensitive centre-zero meter** (a galvanometer or a sensitive voltmeter). Push a bar magnet into the coil: the needle flicks one way. Hold the magnet still inside: the reading drops to zero. Pull it out: the needle flicks the **other** way. Push it in faster: a bigger deflection. (A straight wire moved up and down between the poles of a U-shaped magnet works the same way.)



The size of the induced e.m.f. is bigger when:

- the magnet or wire moves **faster** (the field changes more quickly);
- the magnet is **stronger** (a stronger field);
- the coil has **more turns**.

Turning the magnet round changes the **direction** of the e.m.f., not its size. The current in anything else does not come into it.

Extended only: the direction of the induced e.m.f. The induced e.m.f. always **opposes the change that causes it**. As the N pole of a magnet approaches a coil, the induced current makes the near end of the coil an **N pole**, which **repels** the magnet. As the magnet is pulled away, the near end becomes an **S pole**, which **attracts** it back. You always have to do work to move the magnet, and that work is where the electrical energy comes from. A magnet dropped down a copper tube falls slowly for the same reason: the currents induced in the copper make a field that opposes its fall.

Extended only: the right-hand rule for induced current. For a wire moving across a field, hold your **right** hand like the left-hand rule: **thumb** along the **motion**, **first finger** along the **field** (N to S), **second finger** gives the **induced current**. Check it: the force on the induced current (left-hand rule) always comes out **opposite to the motion**, because it opposes the change.

If the magnet keeps the **same orientation** (it is not turned round), entering the coil from **either** end makes the field through the coil **grow** in the same direction, so the induced current is in the **same** direction both times. When the magnet leaves, the field **shrinks** and the current reverses.

The a.c. generator

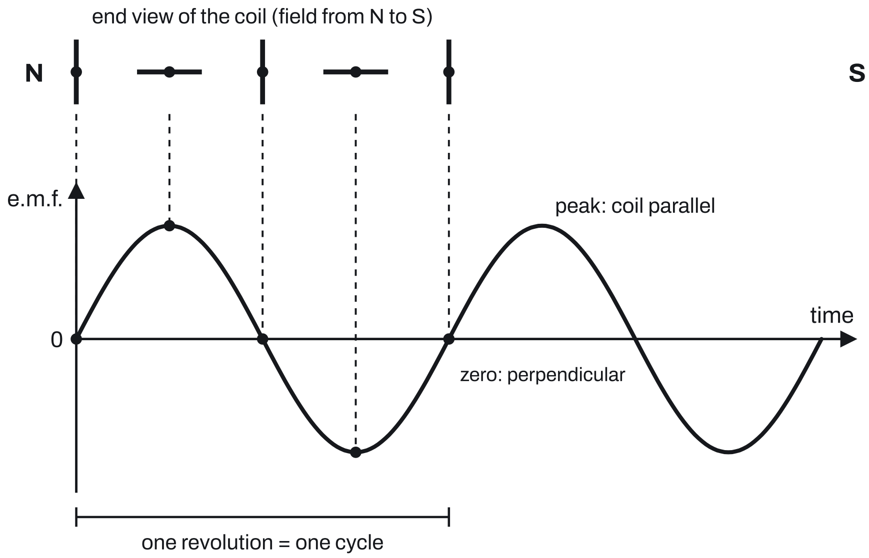
Extended only. A generator uses induction to turn kinetic energy into electrical energy.

Rotating-coil generator. A coil is turned between the poles of a magnet. Its sides cut the field lines, so an e.m.f. is induced. Each end of the coil is joined to its own **slip ring** (a complete ring, not split), and a carbon **brush** presses on each ring. The rings turn with the coil while the brushes stay still, so the coil stays connected to the outside circuit **all the time** and its wires do not twist. Every half turn, each side of the coil starts moving the opposite way through the field, so the induced current **reverses**: the output is **alternating current**.

Rotating-magnet generator (like a bicycle dynamo). A magnet spins next to, or inside, a coil that is fixed in place, often on a soft-iron core that strengthens the field through it. The coil does not move, so it needs **no** slip rings or brushes.

The e.m.f.–time graph is a smooth wave that goes up and down symmetrically.

- The e.m.f. is **zero** when the plane of the coil is **perpendicular** to the field: at that instant its sides move **along** the field lines and cut none.
- The e.m.f. is at a **peak** (or a **trough**) when the plane of the coil is **parallel** to the field: its sides then cut the field lines **fastest**.
- From one peak to the next trough is **half a revolution**; one full cycle (peak and trough) is **one revolution**.
- The **frequency** of the a.c. equals the number of **revolutions per second**. A coil turning 50 times a second gives 50 Hz a.c., with one cycle every $\frac{1}{50} = 0.020$ s.
- Turning the coil **faster** gives **higher peaks** (it cuts field lines faster) **and more cycles** in the same time (a higher frequency). A stronger magnet or more turns gives higher peaks but the same frequency.



The transformer

A **transformer** changes the size of an **alternating voltage**. It has two coils of **insulated copper wire** wound on the same **soft-iron core**:

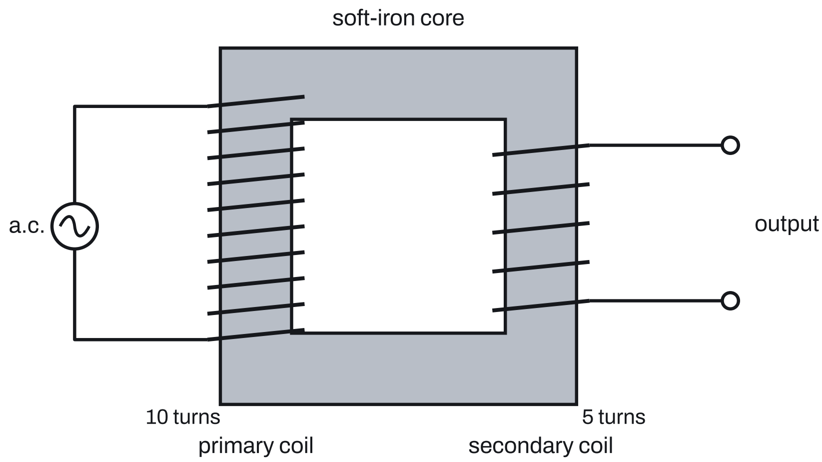
- the **primary coil** (input), connected to the a.c. supply;
- the **secondary coil** (output), connected to the device.

A **step-up** transformer has **more turns on the secondary** than on the primary, so the output voltage is **bigger**. A **step-down** transformer has **fewer turns on the secondary**, so the output voltage is **smaller**. The voltages are in the same ratio as the numbers of turns:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

For example, a transformer with 600 turns on the primary and 30 on the secondary, connected to 120 V a.c., gives $V_s = 120 \times \frac{30}{600} = 6.0$ V.

Copper is used for the coils because it has a **low resistance**, so they waste little energy heating up. Soft iron is used for the core because it is **easily magnetised and demagnetised**, which it must be many times a second.



Extended only: how it works.

1. The **alternating current** in the primary coil makes an **alternating (changing) magnetic field** in the soft-iron core.
2. The core carries this changing field through the **secondary coil**, so the field linking the secondary keeps changing.
3. So an **alternating e.m.f. is induced** in the secondary, and an alternating current flows if the output circuit is complete.

No current flows through the core, and nothing electrical crosses from one coil to the other: only the changing magnetic field links them. On **d.c.** the field in the core is steady, so there is **no** output (just a brief flick at the instant the current is switched on or off). A transformer does not create energy: stepping the voltage **up** steps the current **down**.

Extended only: power in a transformer. If a transformer is 100% efficient, the power going in equals the power coming out:

$$I_p V_p = I_s V_s$$

A 6.0 V lamp taking 3.0 A uses 18 W; if the transformer's primary is on 120 V, the primary current is $\frac{18}{120} = 0.15$ A. Real transformers are nearly 100% efficient; the small loss is thermal energy from the coils and core. A **wireless phone charger** is a transformer with an air gap: an a.c. primary coil in the charging pad and a secondary coil in the phone. With no iron core and a gap between the coils, not all of the changing field reaches the secondary, so it is less efficient.

High-voltage transmission

Power stations are often far from the towns they supply. The electricity is sent along long cables, and the cables have resistance, so they **heat up** and waste energy.

1. A **step-up** transformer at the power station raises the voltage to a very high value (hundreds of thousands of volts).
2. Overhead cables on pylons carry it across the country.
3. **Step-down** transformers near towns and homes bring it back down to a safe voltage (such as 230 V).

Advantages of high-voltage transmission: for the same power, the **current** is **smaller**, so

- **less power is lost** as thermal energy in the cables: transmission is more efficient;
- **thinner, lighter, cheaper cables** can be used, and the **pylons can be further apart**;
- electricity can be sent over **longer distances**.

Extended only: why. The power sent is $P = IV$, so for a fixed power a higher V means a smaller I. The power wasted in cables of resistance R is $P = I^2R$. Because the current is **squared**, cutting it by 10 times cuts the loss by $10^2 = 100$ times. For 100 kW sent through cables of resistance $4.0\ \Omega$:

- at 1000 V: $I = \frac{100\,000}{1000} = 100$ A, and the loss is $100^2 \times 4.0 = 40\,000$ W;
- at $10\,000$ V: $I = 10$ A, and the loss is $10^2 \times 4.0 = 400$ W.

Stepping up the voltage does **not** change the cables' resistance; it only changes the current.

Key facts and formulas

There is no formula sheet for 0625: every equation must be learnt.

Formula	Status
Transformer: $\frac{V_p}{V_s} = \frac{N_p}{N_s}$	Learn it
Extended only: 100%-efficient transformer: $I_pV_p = I_sV_s$	Learn it
Power: $P = IV$	Learn it
Extended only: power lost in cables: $P = I^2R$	Learn it
Step-up: $N_s > N_p$, so $V_s > V_p$; step-down: $N_s < N_p$, so $V_s < V_p$	Learn it
Frequency of a generator's a.c. = revolutions per second; period $= \frac{1}{\text{frequency}}$	Learn it

Formula	Status
Right-hand grip rule: thumb along the current, fingers show the field	Learn it
Solenoid end with the current anticlockwise = N pole; clockwise = S pole	Learn it
Extended only: left-hand rule (force): First finger Field, seCond finger Current, thuMb Motion	Learn it
Extended only: right-hand rule (induced current): thumb motion, first finger field, second finger induced current	Learn it
Induced e.m.f. bigger with: faster movement, stronger magnet, more turns	Learn it
Turning effect on a coil bigger with: more turns, bigger current, stronger magnet	Learn it

How to do it

In the Paper 1–4 questions we have tagged for this topic (241 questions, 205 of them different, 2021–2025), the types came up this often. 46 of the 241 questions mix types, so the counts add up to more than 241.

Question type	Questions
Calculate transformer voltage or turns	43
Draw or identify the magnetic field of a wire or solenoid	36
D.c. motor: turning effect, commutator and parts	31
Transformer construction, materials, step-up and step-down	27
Direction of the force on a current or a moving charge	25
Explain or demonstrate electromagnetic induction	24
Factors that increase the induced e.m.f.	23
Direction of the induced current (it opposes the change)	19
A.c. generator: parts, e.m.f.–time graph, coil position	18
Electromagnets, relays and bells	18
High-voltage transmission and cable power loss	17
Calculate transformer current or power	13
Explain how a transformer works	12

1. Calculate transformer voltage or turns (43 questions)

1. **Write the equation** $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ (a mark on its own on Core papers).
2. **Put in the numbers you know**, then rearrange for the one you want: $V_s = V_p \times \frac{N_s}{N_p}$, or $N_s = N_p \times \frac{V_s}{V_p}$, or $N_p = N_s \times \frac{V_p}{V_s}$.
3. **Check it makes sense**: fewer turns on the secondary means a smaller output voltage (step-down).

For example, to step 240 V down to 12 V with 1000 turns on the primary: $N_s = 1000 \times \frac{12}{240} = 50$ turns.

Variations you will meet:

- **A turns ratio** such as $N_p : N_s = 1 : 25$: the voltage goes up by the same factor, so 9.0 V in gives $9.0 \times 25 = 225$ V out.
- **Which transformer does the job?** (multiple choice). Work out $\frac{V_p}{V_s}$ and pick the option whose $\frac{N_p}{N_s}$ is the same.
- **"Is it step-up or step-down?"** Compare the turns (or the voltages): more turns on the secondary is step-up.
- **Two secondary coils** on one core: treat each one separately with the same primary. With 800 turns on a 240 V primary, a 40-turn secondary gives 12 V, and a secondary giving 9.0 V needs 30 turns.
- **Pick the correct equation** from four: the primary values go together on one side, top and bottom in the same order.
- **A d.c. supply** (a battery) on the primary: the output is 0 **V**, because a steady current makes no changing field.

2. Draw or identify the magnetic field of a wire or solenoid (36 questions)

A straight wire:

1. Draw **concentric circles** round the wire, spaced **further apart** as you go out.
2. Add **arrows** from the right-hand grip rule: anticlockwise for current out of the page, clockwise for current into it.

A solenoid:

1. Inside: **straight, parallel, evenly spaced** lines, running the full length.
2. Outside: lines that **curve round** from one end to the other, **symmetrical** above and below, closed and **never crossing**, like a bar magnet's.
3. Arrows: out of the N end, round the outside, into the S end, and from S to N inside.

Variations you will meet:

- **"Mark a point where the field is strong"**: where the lines are **closest together**: inside the solenoid, or next to the wire. Say that is why.

- **Compasses round a wire or solenoid**: each needle points along the field line through it, N end in the field direction.
- **Bigger current**: stronger field, lines closer together (Extended). **Reversed current**: every arrow and compass reverses; the pattern stays the same.
- **Where is the field strongest along a solenoid?** Inside, and about the same all along the inside; weaker just beyond the ends and weaker still further out (Extended).
- **Which is the N end?** Look at the end: current anticlockwise means N.
- **Describe the experiment**: card, iron filings tapped into place for the pattern, plotting compasses for the direction.
- **What shows the pattern and direction?** A plotting compass (not an ammeter or voltmeter); iron filings show the pattern only.

3. D.c. motor: turning effect, commutator and parts (31 questions)

1. **Increase the turning effect (or speed):** more turns, bigger current (a higher-voltage supply, or less resistance), stronger magnet.
2. **Reverse the rotation:** reverse the current (turn the battery round) **or** swap the magnetic poles; not both.
3. **Extended only:** the **split-ring commutator reverses the current in the coil every half turn**, as the coil passes the position perpendicular to the field, so the turning effect stays in the **same direction** and the coil keeps turning one way. The **brushes** keep a sliding contact between the supply and the turning commutator.

Variations you will meet:

- **Name the parts**: coil, magnets (poles), split-ring commutator, brushes, axle, supply. The **motor symbol** is a circle with M inside.
- **Which device uses the turning effect on a coil?** A d.c. motor (not a generator, relay or transformer).
- **Graphs of turning force** against turns, current or field strength: each one rises as the quantity increases.
- **Extended only: which way does the coil turn?** Use the left-hand rule on each side of the coil that is at right angles to the field: one side goes up, the other down (or one into the page, the other out).
- **Extended only: turning effect and coil position.** Largest with the coil **parallel** to the field; **zero** with the coil **perpendicular** to it. At that point the coil keeps going because of its momentum.
- **Magnets getting weaker** over time: to keep the same speed, increase the current (or add turns).
- **Wrong answers for the commutator**: "keeps the current flowing one way round the coil", "stops the wires tangling" (that is the slip rings' job in a generator), or "changes the size of the current".

4. Transformer construction, materials, step-up and step-down (27 questions)

1. **Two coils** of **insulated copper** wire: a primary and a secondary.
2. Wound on a closed **soft-iron core**, so the core links the two coils.
3. **Step-down**: more turns on the primary. **Step-up**: more turns on the secondary.

4. It works only on **a.c.**, and it changes the **voltage** (a step-up transformer increases the voltage, not the power or the energy).

Variations you will meet:

- **Draw a labelled diagram** of a step-down transformer: a closed iron core, the two coils on opposite sides, **clearly fewer** turns on the secondary, and labels for "primary coil", "secondary coil" and "soft-iron core". A circuit symbol is **not** a diagram of the structure.
- **"Which materials?"** Core: **soft iron** (not copper, aluminium or steel). Coils: **copper** (not iron). Thick copper wire wastes less energy.
- **Where step-up and step-down transformers go** in the grid: step-up at the power station, step-down near homes.
- **Which arrangement steps a voltage up?** An **a.c.** input, an iron core, and more turns on the output coil.

5. Direction of the force on a current or a moving charge (25 questions)

1. **Core:** reversing the current **or** the field reverses the force; reversing **both** leaves it the same. A bigger current or a stronger magnet gives a bigger force.
2. **Extended only:** find the direction with the **left-hand rule**. Field from N to S, current from + to −.
3. The force is at right angles to both the field and the current.

For example, a wire with a current **into** the page, in a field going from left to right, is pushed **towards the bottom of the page** (the diagram in "Understand it").

Variations you will meet:

- **A beam of electrons**: point the second finger **opposite** to their motion. Electrons moving to the right in a field going into the page are pushed **towards the bottom of the page**; positive particles moving the same way would be pushed up.
- **Alternating current in the wire**: the force keeps changing direction, so the wire vibrates. This is how a **loudspeaker** works: the a.c. in the coil makes the cone vibrate and produce sound.
- **A wire on a balance, or a magnet on a balance**: by Newton's third law, if the magnet pushes the wire up, the wire pushes the magnet down, so a balance under the magnet reads more.
- **A rod on two rails** between the poles: it rolls along the rails in the direction of the force.

6. Explain or demonstrate electromagnetic induction (24 questions)

To **explain a reading** on a meter connected to a coil or wire, give the chain:

1. There is **relative movement** between the magnet and the coil (or the wire moves across the field), so the coil **cuts** the magnetic field lines, or the **field linking the coil changes**.
2. So an **e.m.f. is induced** in the coil.
3. The coil is part of a **complete circuit**, so an **induced current** flows.

Variations you will meet:

- **Describe the experiment**: a coil (or wire) connected to a **sensitive** centre-zero meter; move a magnet in and out (or move the wire through a U-shaped magnet's field); the needle deflects while it moves and returns to zero when it stops.
- **"Why is the reading zero?"** Nothing is moving relative to anything else, the field is steady, the wire is moving along the field lines, or the magnet and coil move together.
- **Two coils near each other**: switching the current in one coil on or off changes the field through the other, so the meter on the other flicks briefly; while the current is steady, it reads zero.
- **A magnet oscillating on a spring** into and out of a coil: the needle swings one way, then the other: an alternating current.
- **A lamp lights** when a magnet moves through a coil connected to it: the moving field cuts the coil, an e.m.f. is induced and drives a current through the lamp.

7. Factors that increase the induced e.m.f. (23 questions)

1. Move the magnet (or wire, or coil) **faster**.
2. Use a **stronger magnet**.
3. Use **more turns** on the coil.

Variations you will meet:

- **"Which changes, on their own, increase the e.m.f.?"** Each of the three above does. **Reversing** the magnet or the motion changes only the **direction**. A wider gap between the poles makes the field weaker, so the e.m.f. is smaller.
- **Which gives the biggest reading?** The fastest movement with the strongest magnet.
- **For a generator**: a stronger field, faster rotation, more turns. Faster rotation also raises the frequency.
- **A slower pass** of the same magnet (for example a trolley that has slowed down) gives a **smaller** deflection.

8. Extended only: direction of the induced current (19 questions)

1. **State the rule**: the induced e.m.f. (and current) **opposes the change** that causes it.
2. **For a magnet and a coil**: an approaching pole is **repelled** (the near end of the coil becomes the **same** pole); a leaving pole is **attracted** (the near end becomes the **opposite** pole). Use the solenoid rule (anticlockwise = N) to turn that pole into a current direction.
3. **For a wire moving across a field**: use the **right-hand rule** (thumb motion, first finger field, second finger current). Check it: the left-hand rule force on that current must be **opposite** to the motion.

For example, a wire moved **down** between an N pole on the left and an S pole on the right has a current induced **out of the page**, and the force on that current is **up**, opposing the motion.

Variations you will meet:

- **Reverse the motion or the magnet's pole**: the meter deflects the **other** way. Reverse both: the same way as before.

- **A magnet falling through a copper tube** falls slowly: currents are induced in the copper, and their field **opposes** the magnet's motion. In a plastic tube there are no induced currents, so it falls freely.
- **"In which direction is the force on the wire caused by the induced current?"** Opposite to the way the wire is being moved.
- **A magnet entering a coil from the other end** with the same orientation: the field through the coil still grows in the same direction, so the deflection is in the **same** direction; it is smaller if the magnet is slower.

9. Extended only: a.c. generator: parts, e.m.f.–time graph, coil position (18 questions)

1. **Name the parts**: coil, magnets, **slip rings**, **brushes**. Slip rings keep a **continuous connection** between the turning coil and the outside circuit, without the wires twisting. A **split ring is not** part of an a.c. generator.
2. **Explain how the a.c. is made**: the coil is turned in the field, its sides **cut the field lines**, an **e.m.f. is induced**, and it drives a current round the complete circuit. Every **half turn** each side starts moving the other way through the field, so the current **reverses**.
3. **Read the graph**: one full wave (up and down) is **one revolution**. **Peaks and troughs**: the coil is **parallel** to the field. **Zeros**: the coil is **perpendicular** to the field.

Variations you will meet:

- **Count revolutions**: count the full waves. Two and a half waves is 2.5 revolutions.
- **Match coil positions to times**: at every zero the coil is perpendicular to the field, at every peak and trough it is parallel. Positions half a turn apart look the same from the end.
- **Sketch the graph at double the speed**: peaks **higher** and the waves **closer together** (twice as many in the same time).
- **Frequency and period**: a coil turning 20 times a second gives 20 Hz, with one cycle every $\frac{1}{20} = 0.050$ s.
- **Rotating-magnet generator**: the coil is fixed, so no slip rings; a soft-iron core in the coil makes the field through it stronger.

10. Electromagnets, relays and bells (18 questions)

1. **Core material**: **soft iron**, because it becomes a strong magnet when there is a current and **loses its magnetism** as soon as the current stops. Steel would stay magnetised; copper is not magnetic.
2. **Make it stronger**: a bigger current or more turns.
3. **Explain a bell or relay step by step**: current → solenoid becomes a magnet → it attracts the soft-iron arm (armature) → the arm moves (the striker hits the bell, or the contacts close) → for a bell, the contacts break, there is no current, the magnetism is lost and the springy metal pulls the arm back.

Variations you will meet:

- **Why use a relay?** A small current (or a low-voltage circuit) can safely switch on a circuit with a large current, such as a car's starter motor.

- **Which device uses the magnetic effect of a current?** Relay, loudspeaker, electric bell, electromagnet. **Not** a heater, a lamp, a thermistor or a potential divider.
- **Nails on an electromagnet**: more current picks up more nails; switch off and soft-iron nails fall off.
- **Complete the circuit** with a d.c. supply: draw a **cell** or a **battery** symbol.

11. High-voltage transmission and cable power loss (17 questions)

1. **State two advantages** of high-voltage transmission: a **smaller current**, so **less energy (power) lost** as heat in the cables; **thinner, cheaper cables**; **pylons further apart**; transmission over **longer distances**.
2. **Say where the transformers go**: step-up at the power station, step-down near the users. The voltage is highest in the long-distance cables.
3. **Extended only: explain with equations.** Same power, $P = IV$: higher V means smaller I. The loss is $P = I^2R$, so a smaller current means a much smaller loss.
4. **Extended only: calculate** with $P = I^2R$. For example, 45 W lost in a cable of resistance $0.20\ \Omega$: $I^2 = \dfrac{45}{0.20} = 225$, so $I = 15$ A.

Variations you will meet:

- **"Which situation delivers the most power?"** The **higher** voltage (smaller current) with the **thicker** cables (smaller resistance) wastes the least.
- **Wrong reasons**: "it is faster", "it is safer", "it reduces the resistance of the cables". High voltage is actually more dangerous, which is why the cables are high up on pylons.

12. Extended only: calculate transformer current or power (13 questions)

1. **Write** $I_pV_p = I_sV_s$ (power in = power out, for 100% efficiency).
2. **Substitute and solve** for the unknown current.
3. If you are given a **power** (such as a lamp's rating), use $P = IV$ on the side you know.

For example, a 240 V transformer lights a 6.0 V, 24 W lamp normally. The secondary current is $\dfrac{24}{6.0} = 4.0$ A, and the primary current is $\dfrac{24}{240} = 0.10$ A.

Variations you will meet:

- **Compare the secondary with the primary** for a step-down transformer: the voltage is **smaller**, the current is **larger**. For step-up, the other way round.
- **Two transformers one after the other**: work through them in order; the output of the first is the input of the second.
- **Pick both valid equations** from a list: $\dfrac{V_p}{V_s} = \dfrac{N_p}{N_s}$ and $I_pV_p = I_sV_s$.
- **The load changes**: if the secondary current rises, the primary current rises too, since the power in must still equal the power out.

13. Extended only: explain how a transformer works (12 questions)

Give the chain, one mark for each link:

1. **Alternating current** in the primary coil.
2. This makes an **alternating (changing) magnetic field** in the **soft-iron core**.
3. The core **links** this changing field to the **secondary coil**.
4. An **alternating e.m.f. is induced** in the secondary coil (and a current flows if the circuit is complete).

Variations you will meet:

- **"Which statement is correct?"** Reject any saying current flows **through the core** from one coil to the other; only the magnetic field links them.
- **Why is there no output on d.c.?** The field is steady, so nothing changes and no e.m.f. is induced.
- **A wireless charging pad** is a transformer without an iron core: the primary in the pad, the secondary in the phone. It is less efficient because some of the changing field does not pass through the secondary coil (the air gap), and energy is lost as heat.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

A phone charger contains a transformer. Its primary coil is connected to the 230 V a.c. mains and its secondary coil gives an output of 5.0 V. The secondary coil has 40 turns.

(a) State whether this is a step-up or a step-down transformer, and give a reason. **[1]**

(b) Calculate the number of turns on the primary coil. **[3]**

(c) Describe the construction of this transformer. **[3]**

(d) The transformer is connected to a 230 V d.c. supply by mistake. State the output voltage. **[1]**

(a) Step-down, because the output voltage is smaller than the input voltage (so the secondary has fewer turns). **B1**

(b) $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ **C1**

$N_p = N_s \times \frac{V_p}{V_s} = 40 \times \frac{230}{5.0}$ **C1**

$N_p = 1840$ turns **A1**

(c) Any three of: two coils (primary and secondary) **B1**; made of (insulated) copper wire **B1**; wound on a soft-iron core **B1**; more turns on the primary coil than on the secondary **B1**.

(d) 0 V. **B1** (A steady current makes a steady field, so no e.m.f. is induced.)

Example 2

A bar magnet stands upright on a bench with its N pole at the top. A student holds a coil, connected to a sensitive centre-zero meter, above it and moves the coil down over the magnet. The needle deflects to the right.

(a) Explain why the needle deflects. **[2]**

(b) State what the needle does when:

(i) the coil is held still around the magnet; **[1]**

(ii) the coil is lifted back up off the magnet; **[1]**

(iii) the coil is moved down again, faster. **[1]**

(c) State two other changes that would give a bigger deflection. **[2]**

(d) **Extended only.** State which magnetic pole is induced at the lower end of the coil as it moves down towards the N pole, and explain why. **[2]**

(a) The coil moves relative to the magnet, so the coil cuts the magnetic field lines (the field through it changes). **B1** An e.m.f. is induced in the coil, and it drives a current through the meter because the circuit is complete. **B1**

(b) (i) It returns to zero (no movement, no change in the field). **B1**

(ii) It deflects to the **left**. **B1**

(iii) It deflects to the right, **further** than before. **B1**

(c) A stronger magnet **B1**; more turns on the coil. **B1**

(d) An N pole. **B1** The induced current opposes the change causing it (the coil and the N pole getting closer), so the lower end repels the N pole. **B1** (Only the relative movement matters: moving the coil down is the same as moving the magnet up.)

Example 3

Extended only. A power station sends 2.0 MW of power to a town through cables with a total resistance of $5.0\ \Omega$.

(a) The power is first sent at 25 kV. Calculate the current in the cables and the power lost in them. **[4]**

(b) A step-up transformer raises the voltage to 400 kV. Calculate the new current and the new power lost. **[3]**

(c) The step-up transformer has 1000 turns on its primary coil, which is at 25 kV. Calculate the number of turns on its secondary coil. **[2]**

(d) Explain why the power lost is smaller at the higher voltage. **[2]**

(a) $I = \frac{P}{V} = \frac{2.0 \times 10^6}{25\,000}$ **C1**

$I = 80$ A **A1**

$P_{\text{lost}} = I^2 R = 80^2 \times 5.0$ **C1**

$P_{\text{lost}} = 32\,000$ W (32 kW) **A1**

(b) $I = \frac{2.0 \times 10^6}{400\,000} = 5.0$ A **B1**

$P_{\text{lost}} = 5.0^2 \times 5.0$ **C1** $= 125$ W **A1**

(c) $N_s = N_p \times \frac{V_s}{V_p} = 1000 \times \frac{400\,000}{25\,000}$ **C1** $= 16\,000$ turns **A1**

(d) For the same power, a higher voltage means a smaller current ($P = IV$). **B1** The power lost is I^2R, so a smaller current in the same cables means much less power lost as heat. **B1**

(The current went down 16 times, so the loss went down $16^2 = 256$ times, from $32\,000$ W to 125 W.)

Example 4

Extended only. A simple a.c. generator has a coil that turns at a steady rate of 20 revolutions per second. At time $t = 0$ the plane of the coil is perpendicular to the magnetic field.

(a) Calculate the time for one revolution. **[1]**

(b) State the e.m.f. at $t = 0$, and calculate the time at which it first reaches a peak. Explain your answer. **[3]**

(c) How many complete cycles of the e.m.f. are there in 0.20 s? **[1]**

(d) The coil is now turned at 40 revolutions per second. State two ways the graph of e.m.f. against time changes. **[2]**

(e) State why the coil is connected to the outside circuit by slip rings and not by a split ring. **[1]**

(a) $\frac{1}{20} = 0.050$ s **B1**

(b) The e.m.f. is zero at $t = 0$: the coil's sides are moving along the field lines, not cutting them. **B1** The first peak is a quarter of a revolution later, when the coil is parallel to the field and its sides cut the field lines fastest: **M1**

$t = \frac{0.050}{4} = 0.0125$ s **A1**

(c) $20 \times 0.20 = 4$ cycles. **B1**

(d) The peaks are higher. **B1** The waves are closer together: twice as many cycles in the same time (the period halves to 0.025 s). **B1**

(e) Slip rings keep each end of the coil connected to the same side of the outside circuit, so the output alternates (a split ring would reverse the connections every half turn and give d.c.). **B1**

Common mistakes

- **Confusing the motor and the generator.** A **d.c. motor** has a **split-ring commutator**; an **a.c. generator** has **slip rings**. Examiners see candidates call slip rings "commutators", or say the commutator "carries current from the coil to the circuit".
- **Saying current or e.m.f. passes through the transformer core.** Nothing electrical crosses the core: it carries the **changing magnetic field** from one coil to the other.
- **Forgetting that transformers need a.c.** On d.c. the output is zero. Examiners report many candidates who did not know this.
- **Mixing up core and coil.** The **core** is soft iron; the **coils** are copper. Steel and copper are the usual wrong answers for the core.
- **Drawing the circuit symbol when asked for the structure** of a transformer, or leaving out the iron core, or not making the turns clearly different.
- **Giving "increase the current" as a way to increase an induced e.m.f.** The factors are speed, magnet strength and the number of turns.
- **Saying current is "produced" or "made" instead of induced**, or leaving out the link to a complete circuit.
- **Thinking a high voltage reduces the resistance of the cables.** It reduces the **current**; the resistance stays the same.
- **Solenoid field drawings that lose marks:** lines that cross, stop at the coil, or are not parallel inside; no arrows; or arrows that disagree with each other.
- **Using the wrong hand, or the wrong current.** The left-hand rule is for the force on a current; the right-hand rule is for induced current. Use conventional current (+ to –), and point the current finger backwards for electrons.
- **Describing the commutator as keeping the current in one direction** in the coil. It **reverses** the current in the coil every half turn, so the **turning** stays in one direction.

How to get the marks

- **"Explain" questions on induction, transformers and bells are marked link by link.** Each step of the chain (movement or changing field → e.m.f. induced → current in a complete circuit) is a separate mark, so write every step.
- **Use the key words:** "induced", "cuts the field lines", "changing magnetic field", "soft iron", "slip rings", "split-ring commutator", "opposes the change". Vague phrases such as "the magnet makes electricity" score nothing.
- **Calculations:** write the equation, then the numbers in it, then the answer with a unit (V, A, W or turns). Core papers give a mark for each. Give answers to 2 or 3 significant figures, and convert kV to V and MW to W first.
- **"State two ways"** needs two different factors; "faster" and "quicker" count as one.
- **Field drawings:** lines continuous and smooth, never crossing, symmetrical; at least one arrow on each line, all consistent; closer lines where the field is stronger.
- **Direction questions (Extended):** give the direction in the words of the diagram (towards the top of the page, into the page, clockwise) and, if asked to explain, name the rule you used.
- **"Describe an experiment"** needs the apparatus (coil, magnet, sensitive meter; or card, iron filings, compasses), what you do, and what you see.
- **"Sketch" a graph** means the right shape and the key features (zeros, peaks, how many cycles), not exact values.
- **Multiple choice:** read every option; the wrong ones are often true statements about a different device (a generator instead of a motor, a relay instead of a transformer).

Quick check

1. A transformer changes 240 V a.c. to 6.0 V a.c. Its primary coil has 1600 turns. Calculate the number of turns on its secondary coil.
2. **Extended only.** A toy train set runs from a 100%-efficient transformer plugged into a 110 V supply. The transformer's output drives the train's 9.0 V, 27 W motor normally. Calculate the current in the motor and the current in the primary coil.
3. **Extended only.** A horizontal wire carries a current from left to right across the page. A magnetic field points from the top of the page towards the bottom. State the direction of the force on the wire. Then the field alone is reversed: state the new direction.
4. **Extended only.** A flat copper plate hangs as a pendulum and swings between the poles of a strong magnet. It stops swinging after a few swings, but a plastic plate of the same size keeps swinging for much longer. Explain why.
5. **Extended only.** A power station sends 500 kW at 20 kV through cables of resistance $8.0\ \Omega$. Calculate the power lost in the cables. What would it be at 40 kV?

Answers

1. $N_s = N_p \times \frac{V_s}{V_p} = 1600 \times \frac{6.0}{240} = 40$ turns.
2. Motor current $I_s = \frac{P}{V} = \frac{27}{9.0} = 3.0$ A. Input power = output power $= 27$ W $= I_p \times 110$, so $I_p = \frac{27}{110} = 0.245$ A (3 s.f.).
3. Into the page (left-hand rule: first finger down the page, second finger to the right, thumb into the page). With the field reversed: out of the page.
4. As the copper plate swings into and out of the field, the field through it changes (it cuts the field lines), so e.m.f.s are induced and currents flow in the copper, which is a conductor. The induced currents oppose the change causing them: the force on them acts against the plate's motion, so it slows down, and its kinetic energy is transferred to thermal energy in the copper. Plastic is an insulator, so no currents are induced and only air resistance slows its swing.
5. $I = \frac{P}{V} = \frac{500\,000}{20\,000} = 25$ A, so the loss is $I^2R = 25^2 \times 8.0 = 5000$ W (5.0 kW). At 40 kV the current is 12.5 A and the loss is $12.5^2 \times 8.0 = 1250$ W: doubling the voltage cuts the loss to a quarter.

Past questions to try

- **0625/41/M/J/25 Q8**: the parts of an a.c. generator, then transformers and transmission.
- **0625/42/F/M/25 Q8**: the force on a metal rod carrying a current between two magnets.
- **0625/42/F/M/23 Q8**: which way a motor coil turns, and what the commutator does.
- **0625/41/M/J/22 Q8**: a magnet falling through a copper tube and a plastic tube.