

Electromagnetic induction

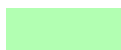
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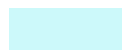
Revision notes for one topic, free to download.

These are the summary notes only. The full edition of this booklet also carries the worked examples, the required practicals and the formula sheets, with every topic in one place.

Colour Codes



Definitions



Diagrams



Notes and warnings



Sub-topic headings

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Define Electromagnetic induction

- inducing a potential difference across a conductor when there is relative movement between the conductor and a magnetic field.

Define Generator effect

- the effect of inducing a p.d. (and a current, if the circuit is complete) by moving a magnet and a conductor relative to each other.

Define Alternator

- a generator with slip rings that produces alternating current (a.c.).

Define Slip rings

- continuous rings that keep each end of the coil connected to the same brush, so the output alternates.

Define Transformer

- a device with two coils on a soft iron core that changes the size of an alternating potential difference.

Define Secondary coil

- the output coil, in which a p.d. is induced.

Define Step-down transformer

- fewer turns on the secondary than the primary; decreases p.d. and increases current.

Define National grid

- the network of transformers, pylons and cables that transfers electrical energy from power stations to consumers.

NOTE

TIER AND SUBJECT TAGGING IN THIS TOPIC

Most of this topic is **Higher Tier only**: 13.1P, 13.2, 13.3P, 13.4P, 13.5, 13.6, 13.7P and 13.11P are all in bold in the specification. Only **13.8, 13.9 and 13.10 (the national grid and the transformer power equation) are examined at both tiers**. Physics-only statements are 13.1P, 13.3P, 13.4P, 13.7P and 13.11P. Note the odd pairing this creates: the **turns-ratio equation (13.7P) is Higher Tier and physics only**, but the **power equation (13.10) is needed by every student, both tiers, including Combined Science**.

Define Induced potential difference

- the p.d. produced across the ends of a conductor by electromagnetic induction.

Define Dynamo

- a generator with a split-ring commutator that produces direct current (d.c.).

Define Split-ring commutator

- a split contact that swaps the coil's connections every half turn, so the output is always in the same direction.

Define Primary coil

- the input coil of a transformer, connected to the a.c. supply.

Define Step-up transformer

- more turns on the secondary than the primary; increases p.d. and decreases current.

Define Turns ratio

- the ratio of the number of turns on the two coils, equal to the ratio of the p.d.s across them.

Define Microphone

- a device that converts pressure variations in a sound wave into variations in current, using induction.

13.1 The generator effect (13.1P)

HIGHER TIER

HT ONLY PHYSICS ONLY If a magnet and a conductor move **relative to each other**, a **potential difference is induced across the conductor**. If the conductor is part of a complete circuit, a **current** flows. (13.1P)

a On a small scale in the laboratory.

- Push a bar magnet **into** a coil of wire connected to a sensitive centre-zero ammeter (or a voltmeter): the needle flicks one way while the magnet is moving.
- Hold the magnet still inside the coil: the reading falls to **zero** — no relative movement, no induced p.d.
- Pull the magnet **out**: the needle flicks the **other** way.
- Move a straight wire up and down between the poles of a magnet, cutting across the field lines, and the same thing happens. Move it *along* the lines and nothing is induced.

b In the large-scale generation of electrical energy.

- In a power station, a turbine (driven by steam from burning fuel or from a nuclear reactor, or by wind or falling water) spins a magnet inside coils of wire — or spins coils inside a magnetic field.
- The continuous relative movement induces a continuously changing p.d., which drives the alternating current supplied to the national grid.

ANALOGY

Electromagnetic induction is the mirror image of the motor effect. In a motor you put **current** in and get **movement** out; in a generator you put **movement** in and get **current** out. A useful mental image: field lines are like blades of grass and the wire is a lawnmower — you only get an output while you are *cutting* through them, and you get more the faster you cut and the thicker the grass. Standing still in the middle of the lawn produces nothing.

	Motor effect (Topic 12)	Generator effect (Topic 13)
Input	Current in a wire in a magnetic field	Movement of a conductor in a magnetic field
Output	Force, so movement	Induced potential difference, so current
Energy transfer	Electrical → kinetic	Kinetic → electrical
Rule used	Fleming's left -hand rule	(Right-hand rule — not required by this spec)
Device	Electric motor, loudspeaker	Alternator, dynamo, microphone

13.2 Factors affecting the induced potential difference (13.2)

HIGHER TIER

HT ONLY The size of the induced potential difference increases if you:

- move the magnet or conductor **faster** (a faster rate of change of the field);
- use a **stronger magnet** (greater magnetic flux density);
- use **more turns** on the coil;
- use a coil of **larger area**, or add an iron core.

HT ONLY The direction of the induced potential difference is reversed if you:

- reverse the **direction of movement** (push the magnet in rather than pull it out);
- reverse the **poles of the magnet** (north pole first rather than south pole first).

HT ONLY The induced field opposes the original change. The induced current itself creates a magnetic field, and that field always acts to **oppose the change that produced it**.

- Push a north pole into a coil and the near end of the coil becomes a **north** pole, pushing back against the magnet.
- Pull the magnet out and the near end becomes a **south** pole, trying to pull it back.
- Either way you must do **work** against this opposing force — that is where the electrical energy comes from, so energy is conserved. If the induced field helped the motion instead, you would get energy from nothing.

13.3 Alternators and dynamos (13.3P)

HIGHER TIER

HT ONLY PHYSICS ONLY Both are generators. A coil is rotated in a magnetic field (or a magnet is rotated inside coils); the difference is only in **how the output is taken off the coil**.

Alternator — generates a.c.

- Uses two **slip rings** with brushes. Each end of the coil stays connected to the same brush all the time.
- As the coil turns, each side moves first upwards through the field, then downwards, so the induced p.d. **reverses every half turn**.
- Output: an **alternating** p.d. and current, shown as a sine curve crossing the time axis twice per rotation.

Dynamo — generates d.c.

- Uses a **split-ring commutator**. The two halves of the ring swap contact with the brushes every half turn, exactly as the coil's induced p.d. is about to reverse.
- The swap cancels the reversal, so the output is always in the **same direction**.
- Output: a **direct** p.d. that varies in size (a series of humps all above the axis) but never changes direction.

For both: the p.d. is at a maximum when the coil is parallel to the field (the sides are then moving at right angles to the field lines, cutting them fastest) and zero when the coil is at right angles to the field (the sides are then moving along the field lines, cutting none). Turning the coil faster increases both the **peak p.d.** and the **frequency**.

13.4 Microphones, loudspeakers and headphones (13.4P)

HIGHER TIER

HT ONLY PHYSICS ONLY A moving-coil microphone converts pressure variations in a sound wave into variations in current.

1. A sound wave is a series of **pressure variations** (compressions and rarefactions) in the air.
2. These pressure changes make a **diaphragm** vibrate backwards and forwards.
3. A coil of wire attached to the diaphragm sits around a permanent magnet, so the coil **moves relative to the magnetic field**.
4. This relative movement **induces a potential difference** across the coil (electromagnetic induction).
5. The p.d., and so the current, varies in step with the sound wave: a **louder** sound gives a larger amplitude of vibration and so a larger current, and a **higher-pitched** sound gives a higher-frequency current.

HT ONLY PHYSICS ONLY Loudspeakers and headphones are the reverse process, and use the motor effect rather than induction.

1. A varying (alternating) current from the amplifier passes through a coil attached to a cone, sitting in the field of a permanent magnet.
2. The current-carrying coil in the magnetic field experiences a **force** (the motor effect), whose direction reverses whenever the current reverses.
3. The coil and cone therefore **vibrate**, pushing and pulling on the air and creating pressure variations — a sound wave.
4. The **frequency** of the current sets the pitch; the **amplitude** of the current sets the loudness.

13.5 How a transformer works (13.5, 13.6)

HT ONLY A **transformer** is two coils of insulated wire wound on a **soft iron core**. There is no electrical connection between them.

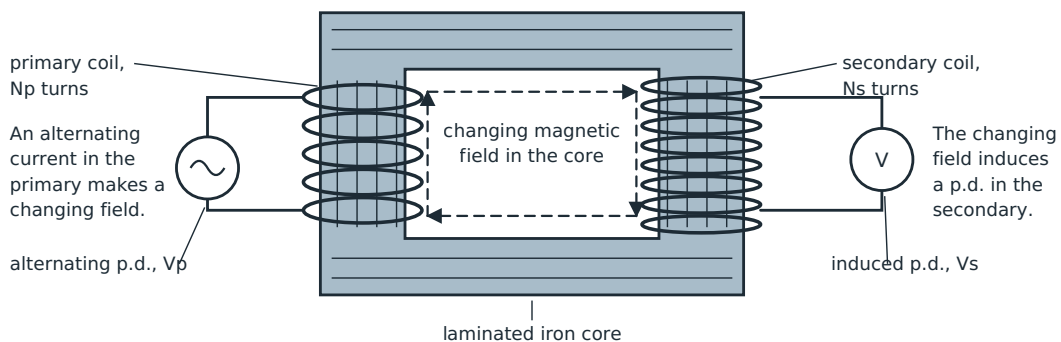
HT ONLY How an **alternating current** in one circuit induces a **current** in another (13.5):

1. An **alternating** current in the **primary coil** produces a magnetic field that is constantly **changing** in size and direction.
2. The **soft iron core** is easily magnetised and demagnetised, so it carries this changing field round to the secondary coil with very little loss.
3. The changing magnetic field through the **secondary coil** induces an **alternating potential difference** across it (electromagnetic induction).
4. If the secondary circuit is complete, an alternating current flows in it.

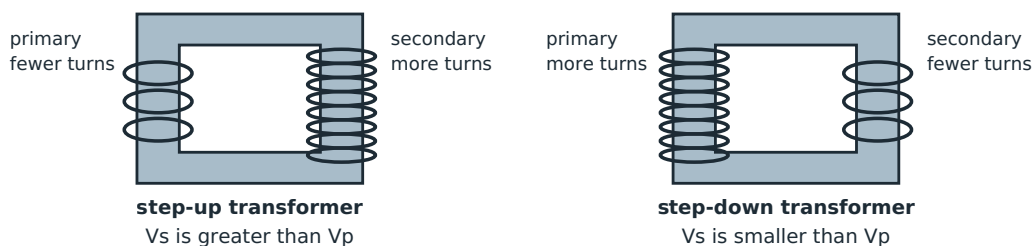
Step-up and step-down transformers

Higher tier only (see note)

A basic transformer



Step-up and step-down transformers



The transformer equations

$$V_p / V_s = N_p / N_s$$

V_p and V_s are the potential differences across the coils, in volts, V.

N_p and N_s are the numbers of turns.

Iron is used because it is easily magnetised.

Note: the 'Higher tier only' badge above applies to the turns-ratio equation and panels A and B, not to 13.10.

$$V_s \times I_s = V_p \times I_p$$

power output (secondary) = power input (primary), if the transformer is 100% efficient.
power, in watts, W; current, I, in amperes, A
A transformer only works with a.c., not d.c.

Both tiers (13.10) — this equation is not Higher Tier only.

HIGHER TIER

HT ONLY A transformer can change the size of an alternating voltage (potential difference) (13.6) — the size of the output depends on the numbers of turns on the two coils.

WATCH OUT

Transformers only work with a.c. A steady direct current would produce a steady, unchanging magnetic field, and an unchanging field induces nothing in the secondary coil. If a question shows a transformer connected to a battery, the answer is "no output".

13.6 The turns-ratio equation (13.7P)

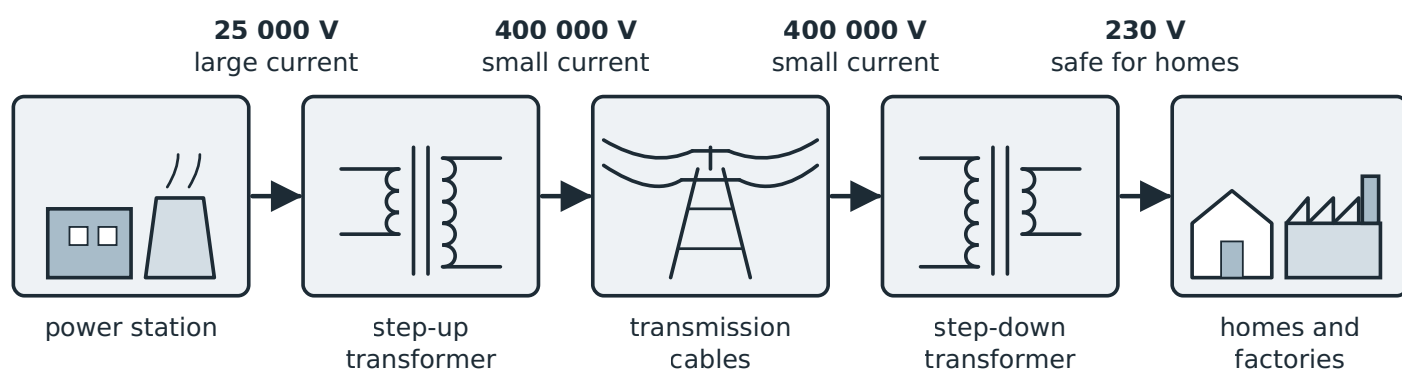
13.7 The transformer power equation (13.10)

13.8 The national grid (13.8, 13.9)

The **national grid** transfers electrical energy from power stations to homes, shops and factories.

- **Step-up transformers** are used **at the power station**, raising the p.d. from about 25 000 V to 132 000 V or more for the transmission cables.
- **Step-down transformers** are used at substations **in each locality**, lowering the p.d. in stages to 230 V for domestic use.
- **Why (13.8):** transmitting at a high p.d. means the current in the cables is small. A small current means much less energy is wasted heating the cables, so the **efficiency of transmission is improved** and less fuel is needed.
- The p.d. must be reduced again locally because hundreds of thousands of volts would be extremely dangerous in homes, and domestic appliances are designed for 230 V.

The national grid



Reducing the energy dissipated in the cables

- The transmission cables have resistance, so some energy is dissipated by heating as current flows.
- A transformer does not change the power that is transferred: $P = VI$ stays the same. So if the p.d. is stepped up, the current is stepped down.
- The power wasted in the cables is $P = I^2R$, so it depends on the square of the current: halving the current cuts the wasted power to a quarter.
- A high potential difference and a low current therefore make the National Grid an efficient way of transferring energy.

$$P = I^2 R$$

P = power wasted in the cables, watts (W)

I = current in the cables, amperes (A)

R = resistance of the cables, ohms (Ω)

Stepping the potential difference up 16 times steps the current down 16 times, so the power wasted in the cables falls by $16^2 = 256$ times.

	Step-up transformer	Step-down transformer
Turns	More turns on the secondary than the primary	Fewer turns on the secondary than the primary
Effect on p.d.	Increases it	Decreases it
Effect on current	Decreases it	Increases it
Where in the grid	At the power station, before transmission	At local substations, before consumers
Why	Low current in the cables reduces heat loss	Makes the supply safe and usable at 230 V

13.9 Why high-voltage transmission works — the $P = I^2R$ argument (13.11P)

HT ONLY PHYSICS ONLY Statement 13.11P asks you to explain the advantages of transmission in high-voltage cables **using the equations of 10.29, 10.31, 13.7P and 13.10**. These are the three you need alongside the turns-ratio equation.

The argument in words.

1. A power station generates a fixed **power**, $P = I \times V$.
2. A **step-up transformer** raises V . Since the power is fixed (and $V_p/I_p = V_s/I_s$), raising V must **reduce I** by the same factor.
3. The power wasted heating the cables is $P = I^2 \times R$. The cables' resistance R is fixed by their length and thickness, so the waste depends on the **square** of the current.
4. Reducing the current by a factor of 100 reduces the wasted power by a factor of $100^2 = 10\,000$.
5. Less energy wasted per second means more of the generated energy reaches the consumer — the transmission is far more **efficient**, and over time ($E = P \times t$) far less fuel is burnt.
6. A **step-down transformer** then lowers the p.d. again for safe local use.

Use of mathematics —

HT ONLY apply the equations linking the p.d.s and numbers of turns in the two

coils of a transformer to the currents and the power transfer involved, and relate these to the advantages of transmission at high voltages (maths skills 1c, 3b, 3c); make calculations using ratios and proportional reasoning (1c, 3c).