How are fields used to move electricity?

Flux, induced EMF

- **calculate magnetic flux when the magnetic field is perpendicular to the area, and describe the qualitative effect of differing angles between the area and the field:**

  $\Phi_B = B^{\perp} A.$

- **investigate and analyse theoretically and practically the generation of electromotive force (emf) including AC voltage and calculations using induced emf,** $\varepsilon = -N\frac{\Delta\phi_B}{\Delta t}$ **, with reference to:**

  – rate of change of magnetic flux

  – number of loops through which the flux passes

  – direction of the induced emf in a coil.

- **explain the production of DC voltage in DC generators and AC voltage in alternators, including the use of split ring commutators and slip rings respectively.**

Paper	Multiple choice	Short Answer	Idea	Marks	%	Type
2022	2		Frequency from graph	1	73%	Concept
	5		Effect of doubling rotation	1	62%	Concept
		4	Direction of induced current	6	43%	Concept
		6a	Φ = BA	2	78%	Calculation
		6b	EMF = $-n\frac{\Delta\Phi}{\Delta t}$	3	61%	Calculation
2022 NHT	6		Direction of induced current	1	NA	Concept
		4a	Direction of induced current	1	NA	Concept
		4b	EMF = $-n\frac{\Delta\Phi}{\Delta t}$	3	NA	Calculation
		4c	Effect on output, Δn, Δf	2	NA	Concept
		5	Induced current in a coil	2	NA	Explanation
2021	6		EMF = $-n\frac{\Delta\Phi}{\Delta t}$	1	73%	Calculation
	8		Split ring commutator	1	51%	Concept
		6a	AC generator, EMF graph	4	63%	Calculation
		6b	Slip rings	1	54%	Explanation
		6c i	AC generator to DC output	1	55%	Explanation
		6c ii	DC generator output graph	2	64%	Concept

2021 NHT	8		AC generator, ∆input	1	NA	Concept
	9		Induced current in a coil	1	NA	Concept
		5	Generator, DC output, graph	3	NA	Concept
		6a	Role of slip rings	2	NA	Explanation
		6b	Φ = BA	2	NA	Calculation
		6c	$f = \frac{1}{T}$, graph interpretation	1	NA	Calculation
		6d	Effect on output, ∆rotation	2	NA	Concept
2020	5		Φ = BA	1	53%	Calculation
	6		$EMF = -n\frac{\Delta\Phi}{\Delta t}$	1	89%	Calculation
		5a	Induced EMF direction	1	34%	Concept
		5b	Induced EMF magnitude	3	61%	Calculation
		5c	Induced EMF sketch of graph	3	36%	Concept
		5d	Modification for improvement	2	85%	Explanation
		6a	∆Φ	1	61%	Concept
		6b	Direction of induced current	3	42%	Explanation
		6c	Direction of induced current	2	28%	Explanation
2019	7		Effect of ∆rotation	1	60%	Concept
	8		Flux/Voltage graphs	1	63%	Concept
		7a	Alternator	1	44%	Concept
		7b i	Φ	1	82%	Calculation
		7b ii	Concept	1	67%	Concept
		7c	Period	1	81%	Calculation
		7d	Φ_{max}	2	81%	Calculation
		7e	EMF	2	51%	Calculation
		7f	Concept	2	76%	Explanation
		7g	Voltage output graph	2	77%	Concept
2019 NHT	7		Effect of ∆rotation	1	NA	Concept
		2a	$EMF = -n\frac{\Delta\Phi}{\Delta t}$	3	NA	Calculation
		2b	Induced EMF graph	2	NA	Concept
2018		2a	$EMF = -n\frac{\Delta\Phi}{\Delta t}$	3	80%	Calculation
		2b	Induced EMF graph	3	47%	Concept
		4b	Effect of ∆rotation	2	60%	Concept
2018 NHT	4		EMF vs t graph	1	NA	Concept
		4a	Φ vs t graph	2	NA	Concept
		4b	EMF vs t graph	2	NA	Concept

		4c	$EMF = -n \frac{\Delta\Phi}{\Delta t}$	2	NA	Calculation
		4d	Concept explanation	3	NA	Explanation
2017	6		EMF vs t graph	1	60%	Concept
		5a	Φ = BA	3	73%	Calculation
		5b	$EMF = -n \frac{\Delta\Phi}{\Delta t}$	3	53%	Calculation
		5c	Commutator role	2	67%	Concept

Flux, Induced EMF questions can be grouped into the following ideas.

Concepts
- Φ = BA — Worked example 1
- Φ = BA, B & A parallel — Worked example 2
- $EMF = n \frac{\Delta\Phi}{\Delta t}$, Faraday's law — Worked example 6
- Lenz's law — Worked example 5

Graphs
- Φ vs t — Worked example 3
- EMF vs t graph, from ΔΦ — Worked example 4
- EMF vs t graph, AC — Worked example 7
- EMF vs t graph, frequency, period — Worked example 9
- EMF vs t graph, effects of changes — Worked example 10
- EMF vs t graph, DC — Worked example 11

Generators questions can be grouped into the following ideas.

Generator output
- Role of slip rings — Worked example 8
- Converting between DC/AC — Worked example 12

Magnetic flux

Magnetic flux (Φ_B) is a measure of the amount of magnetic field passing through an area.

$\Phi_B = B_\perp \times A$

$\therefore B_\perp = \frac{\Phi_B}{A}$ where $B_\perp$ is the magnetic field strength (T - Tesla) perpendicular to the given area A and Φ_B is the magnetic flux (Wb - Weber) and A the area (m^2).

Electromagnetic Induction in a wire

Electromagnetic Induction is the creation of an electric current in a conductor moving across a magnetic field. This current can cause an EMF to be produced between the ends of the conductor. Induced current is achieved by either moving the conductor relative to the magnetic field or changing the strength of the magnetic field surrounding the conductor.

Faraday's law of electromagnetic induction (name not on course)

The **magnitude** of the induced EMF is directly proportional to the rate of change of magnetic flux or the rate at which magnetic flux is cut for a wire moving across magnetic field lines.

The induced EMF = $\frac{\Delta\Phi_B}{\Delta t}$

EMF induced by changing flux in a loop

Wire can be used to produce a loop, and there is always an EMF generated in a conducting loop in which there is a changing magnetic flux. If the coil has 'n' turns then the total EMF = n $\frac{\Delta\Phi_B}{\Delta t}$

Lenz's Law.

The **direction** of the induced EMF is the same as that of a current whose magnetic action would oppose the flux change. EMF = -n $\frac{\Delta\Phi_B}{\Delta t}$

n: number of turns, ϕ magnetic flux (Weber), -ve means that the EMF 'opposes the change in flux'.

Induced EMF in a rotating coil

The EMF generated by the rotating coil, EMF = -n $\frac{\Delta\Phi_B}{\Delta t}$ the result obtained from this is the negative of the gradient of the flux v time graph.

Problem solving process

There is a simple 4 step process to answering these questions

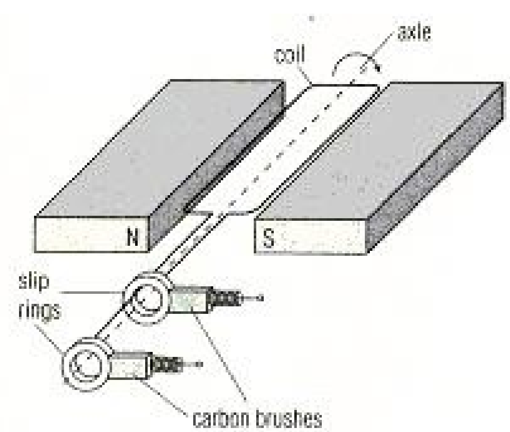
1. Identify the direction of the initial flux
2. Indicate how it is changing, use language of 'increasing/decreasing'
3. State; "The induced EMF will create a current (if the circuit is complete), that has a field that will oppose the change in flux".
4. Apply to the question that you are responding to.

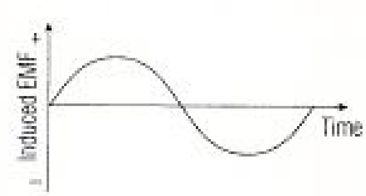
AC Generators (Alternators)

An AC generator has a rotating coil in a magnetic field, or a rotating magnetic field positioned inside a coil. Instead of a commutator, slip rings are used to keep contact with the brushes and the direction of the induced EMF changes every half cycle and an AC output is produced.

Slip rings are used, where one end of the loop is always attached to the same ring, so that the output varies sinusoidally, ie AC output.

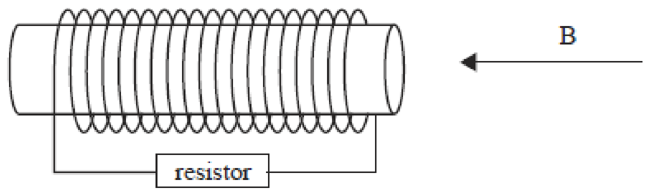
If a split ring commutator is used the output is DC.





[Worked example 1: Concept: Φ = BA.]

A coil is wound around a cardboard cylinder, as shown in Figure 19. The cross-sectional area of the coil is 0.0060 m^2. There are 1000 turns in the coil (not all are shown in the diagram).



The axis of the coil is immersed in a uniform external magnetic field of strength 0.0050 T and its direction is shown by the arrow labelled B in the figure above.

2016 Question 15a, 2 marks

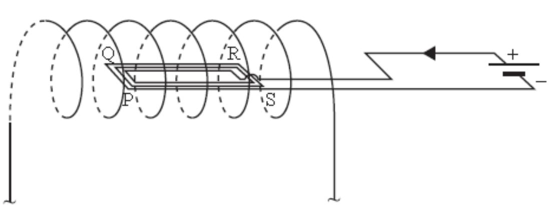
Calculate the magnitude of the flux through the first turn of the coil. Include an appropriate unit.

Solution	**Current study design:**
Flux is given by BA ∴ **Φ = BA** ∴ **Φ = 0.0050 × 0.0060** ∴ **$\Phi = 3.0 \times 10^{-5}$ Wb (ANS), (73%)**	**2021 NHT Question 6b** **2020 Question 5 (53%)** **2020 Question 6a (61%)** **2019 Question 7d (81%)** **2017 Question 5a (73%)**

[Worked example 2: Concept: Φ = BA, B & A parallel.]

A rectangular loop of wire, PQRS, of sides PQ = 4.0 cm and QR = 8.0 cm, is placed inside the solenoid as shown below. The loop has 3 turns of wire. A current of 4.0 amps flows in the loop, in the direction indicated by the arrow.

The uniform magnetic field strength inside the solenoid is 5.0×10^{-2} T.



2010 Question 2, 2 marks

What is the magnetic flux threading the loop? Explain your answer.

Solution	**Current study design:**

Inside the loop the magnetic field is parallel to the loop. Therefore there is not any flux threading the loop.

∴ **0 (ANS), (45%)**

2022 Question 6a (78%)

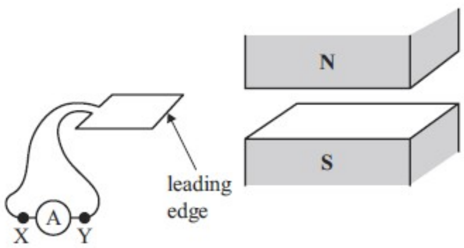
2019 Question 7b i (82%)

2019 Question 7b ii (67%)

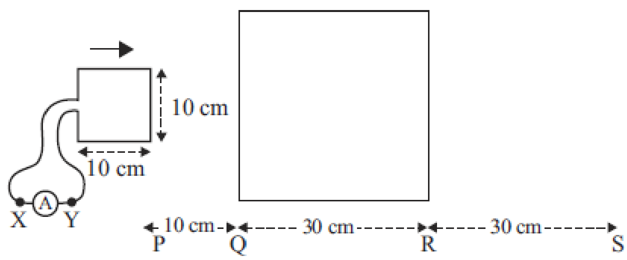
Worked example 3: Graphs: Φ vs t.

A square loop of side 10 cm is allowed to move horizontally through a region of a magnetic field. This is shown below.

Assume the magnetic field is uniform and does not extend beyond the limits of the magnets.

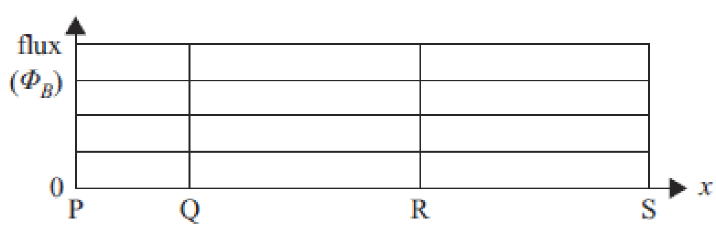


The arrangement is shown below as viewed from above.

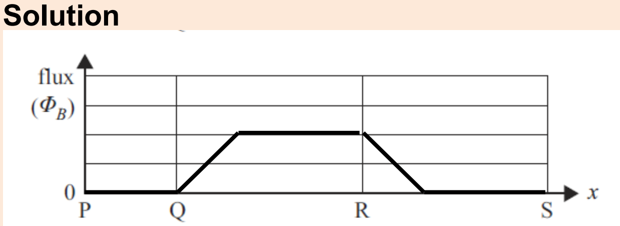


2017 NHT Question 14a, 2 marks

On the graph provided below, sketch the magnitude of the flux threading the loop as the loop moves with its leading edge moving from P to S.



Solution



Current study design:

2022 Question 2 (73%)

2019 Question 8 (63%)

2018 NHT Question 4a

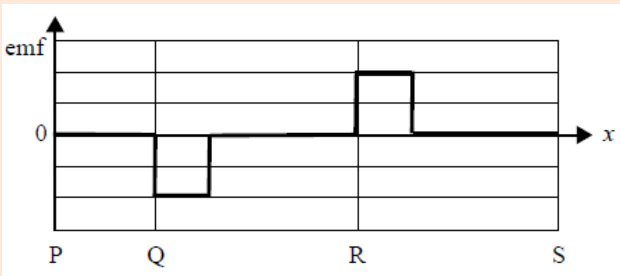
The flux is zero until the leading edge reaches the field. Then the flux increases at a constant rate to a maximum constant value. When the leading edge of the loop reaches the right hand end of the field, the flux starts to decrease at the same rate until it reaches zero.

Worked example 4: Graphs: EMF vs t, from $\Delta\Phi$.

2017 NHT Question 14b, 2 marks

On the graph provided below, sketch the induced emf as the loop moves with its leading edge moving from P to S.

Solution



The induced EMF is the negative gradient of the flux vs time graph.

Current study design:

2022 Question 4 (43%)

2018 Question 2b (47%)

2018 NHT Question 4b

2017 Question 6 (60%)

Worked example 5: Concept: EMF = n $\frac{\Delta\Phi}{\Delta t}$, Lenz's law.

2017 NHT Question 14c, 4 marks

Making reference to any relevant physical law, determine whether the current will flow from X to Y or from Y to X through the meter A as the loop moves into the magnetic field. Explain your answer.

Solution

The initial flux through the loop is downwards and increasing.
Lenz's law gives that the induced current will produce a field that will create an increasing, upwards flux to oppose the change in flux. Use the right hand rule to determine that the current will flow anticlockwise through the loop, to produce a field upwards, and hence from X to Y through meter A.

∴ X to Y. (ANS)

Current study design:

2022 NHT Question 6

2022 NHT Question 4a

2022 NHT Question 5

2021 NHT Question 9

2020 Question 5a (34%)

2020 Question 6b (42%)

2020 Question 6c (28%)

2018 NHT Question 4d

Worked example 6: Concept: EMF = n $\frac{\Delta\Phi}{\Delta t}$, Faraday's law.

2017 NHT Question 14d, 3 marks

The magnetic field has a uniform value of 2.0×10^{-3} T and the loop has a resistance of 2.0 Ω.

The loop takes 0.50 s to move into the magnetic field.

Calculate the average current in the meter A as the loop moves into the magnetic field. Show your working.

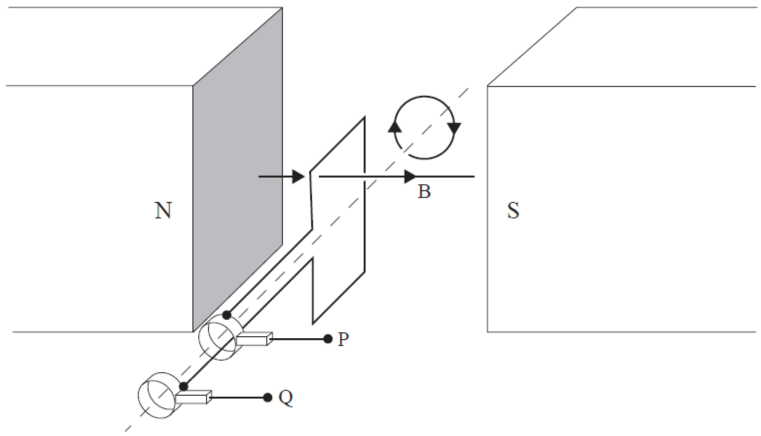
Solution	**Current study design:**
Use $\xi = -n \frac{\Delta\Phi}{\Delta t}$	2022 Question 6b (61%)
$= -n \times B \frac{\Delta A}{\Delta t}$	**2022 NHT Question 4b**
$= -2.0 \times 10^{-3} \times \frac{10 \times 10^{-2}}{0.50}$	**2021 Question 6 (73%)**
$= -4.0 \times 10^{-5}$ V	**2020 Question 6 (89%)**
Use V = iR	**2020 Question 5b (61%)**
$\therefore 4.0 \times 10^{-5} = i \times 2.0$	**2019 Question 7e (51%)**
$\therefore i = 2.0 \times 10^{-5}$ A (ANS)	**2019 NHT Question 2a**
	2018 Question 2a (80%)
	2018 NHT Question 4c
	2017 Question 5b (53%)

Worked example 7: Graphs: EMF vs t, (AC).

Emily and Gerry have been studying generators and alternators. They have constructed the device shown below.

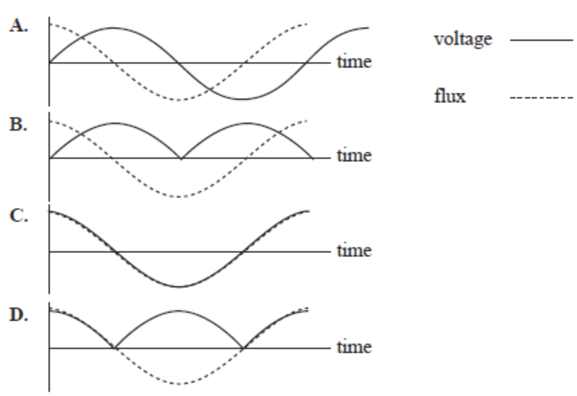
The rectangular coil, which is a single loop of area of 9.0×10^{-4} m^2, is rotated in the direction shown, in a uniform magnetic field with a direction indicated by **B**.

The coil is completely contained in the magnetic field.



They tested the device by firstly connecting an oscilloscope between the terminals P and Q, and then rotating the coil at a constant rate, in the uniform field B, in the direction shown.

The figure below shows graphs of the magnetic flux through the coil and of the voltage measured between the terminals.



2010 Question 6, 2 marks

Which one of the graphs above best represents the voltage observed on the oscilloscope?

Solution	**Current study design:**
When the flux is at a maximum, the gradient of the flux vs time graph is zero, therefore the induced voltage is zero. When the flux is zero, The gradient of the flux vs time graph is a maximum, therefore the induced voltage is a maximum. The slip rings ensure AC output. ∴A (ANS), (75%)	**2021 Question 6a (63%)** **2019 NHT Question 2b**

Worked example 8: Generator output: Role of slip rings.

2010 Question 7, 3 marks

Explain the difference in function between a split-ring commutator and slip rings. Describe the situations in which a split-ring commutator and slip rings are used.

Solution

With slip rings, each ring stays connected to either P or Q through-out the cycle. This produces an AC output.
A split ring swaps the connection to P and Q twice every cycle, i.e. reversing the direction of the current every half cycle. The split ring produces a DC output.
In general, slip rings are used to produce AC, whilst the split ring is used to produce DC. (63%)

Current study design:

2021 Question 8 (51%)

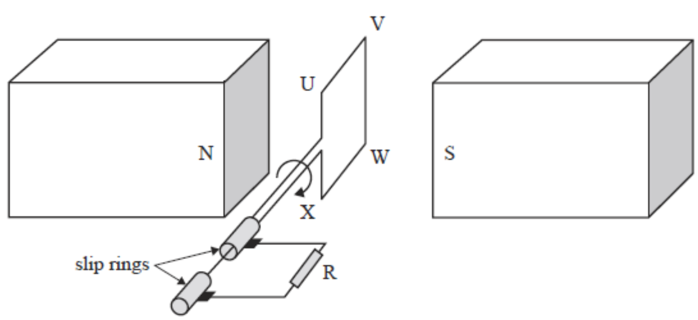
2021 Question 6b (54%)

2021 NHT Question 6a

2019 Question 7a (44%)

Worked example 9: Graphs: EMF vs t, frequency, period.

Samira and Mark construct a simple alternator, as shown below.



When the coil is rotating steadily, it takes 40 ms for each complete rotation and produces a peak emf of 3.5 V.

2016 Question 17a, 2 marks

Calculate the frequency of the AC emf.

Solution

Use $f = \frac{1}{T}$

$\therefore f = \frac{1}{40 \times 10^{-3}}$

$\therefore f = 25$ Hz (ANS), (70%)

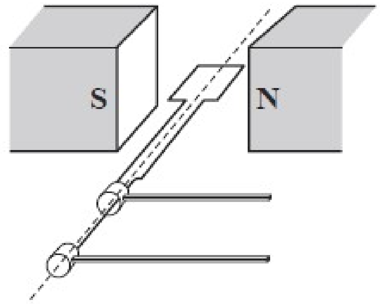
Current study design:

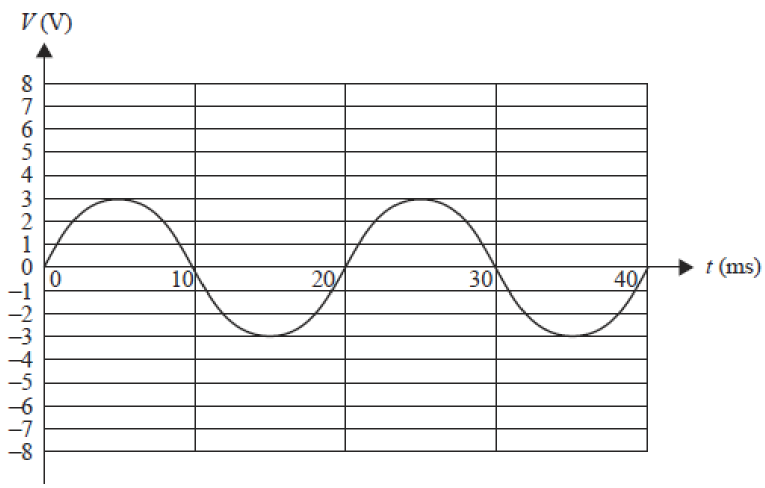
2021 NHT Question 6c

2019 Question 7c (85%)

Worked example 10: Graphs: EMF vs t, effect of changes.

A student constructs a simple alternator. The alternator is shown below. Its output signal, as seen on an oscilloscope, is shown below.





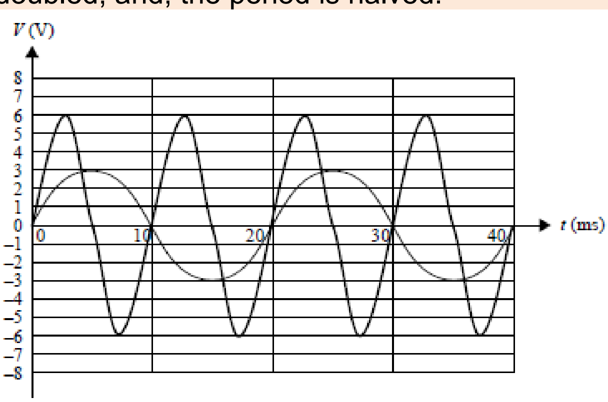
2017 NHT Question 16b, 3 marks

The speed of rotation is now doubled.

On the figure above, sketch what the student will now see on the oscilloscope.

Solution

When the speed of rotation is doubled, the EMF (which is the rate of change of the flux) is doubled, and, the period is halved.



Current study design:

2022 Question 5 (62%)

2022 NHT Question 4c

2021 NHT Question 8

2021 NHT Question 6d

2020 Question 5d, (85%)

2019 Question 7 (60%)

2019 Question 7f, (76%)

2019 NHT Question 7

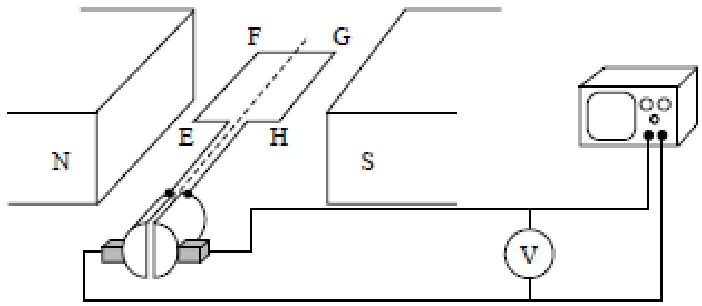
2018 Question 4b (60%)

Worked example 11: Graphs: EMF vs t, DC.

Students have a model that can be used as a motor or generator, depending on the connections used.

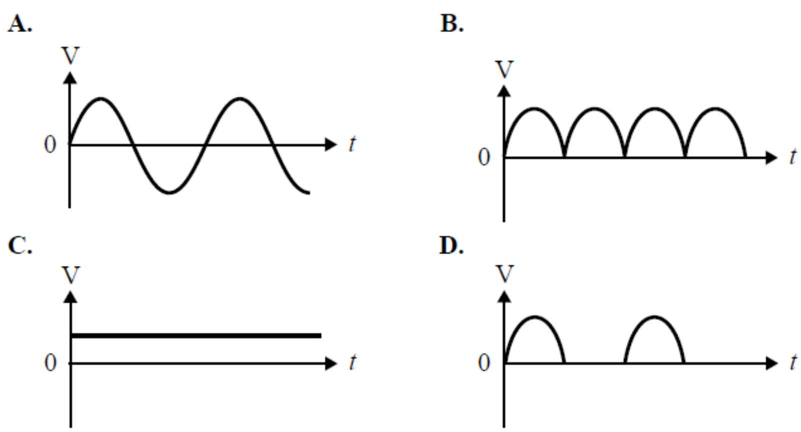
The model is now set up as a DC generator, with the output connected to a voltmeter and oscilloscope via a commutator, as shown below, with the same coil of side length 4.0 cm and 10 turns, and a uniform magnetic field of 2.0×10^{-3} tesla.

The shaft is rotated by hand.



2015 Question 12b, 1 mark

Which one of the following graphs (**A.–D.**) best shows the voltage output as viewed on the oscilloscope as the coil rotates steadily? (At t = 0, the coil is horizontal, as shown.)



Solution

The split ring commutator will reverse the direction of the output every half cycle.

∴ B (ANS), (80%)

You may note that the answer should have started at a maximum, since the initial flux is zero. B is the 'best' answer, even if it is not strictly correct.

Current study design:

2021 Question 6c ii (64%)

2021 NHT Question 5

2020 Question 5c (36%)

2019 Question 7g (77%)

2018 NHT Question 4

2017 Question 5c (67%)

Worked example 12: Generator output: Converting to/from DC.

2015 Question 12d, 3 marks

The students wish to convert this DC generator into an AC generator.

Describe the change or changes the student would have to make to achieve this. Explain your answer.

Solution	**Current study design:**
Replace the split ring commutator with a slip rings. The slip rings maintain constant connection throughout the rotation. **The direction of the flux through the loop reverses every half turn, which results in AC being generated in the loop. (47%)**	**2021 Question 6c i (55%)**