Teaching ideas for Topic 11: Electromagnetic induction (HL)

This topic is divided into three sections. The first two sections (Subtopic **11.1**: Electromagnetic induction and Subtopic **11.2**: Power generation and transmission) are about the physics of electromagnetic induction, its application to the generation of electricity and alternating current circuits. There is a good cross-over here with the material in Topic **8**: Energy production. The third section (Subtopic **11.3**: Capacitance) deals with circuits containing capacitors.

Some useful points to consider are:

- Conceptually, this topic is demanding for students. Teaching this some time after you have taught Fleming's left-hand rule and magnetic forces caused by catapult fields may help students not to confuse these two different aspects of electromagnetism.
- The section about R–C circuits seems slightly out of place in the syllabus because it is not related to electromagnetic induction closely enough for students to see why it is in this part of the course. Teachers may like to teach this section of the topic separately, as it is a topic that can stand alone. Once students are happy with electrical circuits (especially the ideas of $V = IR$, $Q = \int I\Delta t$, and $E = Vq$) and electrical fields (from Topic **5**: Electricity and magnetism and Topic **10**: Fields), this section should be easy to do.
- If you have covered Topic **7**: Atomic, nuclear and particle physics already, then students will be familiar with the mathematics of an exponential relationship. If not, then teaching the section about capacitors will require work on this important piece of mathematics. The idea of a time constant is crucial, but the formal derivation of an exponential equation, from a first order differential equation, is not required. This links directly with aim 3 of the group 4 aims in the IB Physics guide.

Ideas for teaching the topic

- Faraday's observations from his experiments conducted around 1831, with primitive equipment, allowed him to formulate his ideas of electromagnetic induction into the laws we now know. This deductive approach reflects very clearly the way in which science learns and is a powerful idea for students to appreciate. This links very nicely with the Nature of science and natural science as an area of knowledge in the Theory of knowledge (TOK) course.

  Teachers might like to deliver this topic by using a purely empirical approach: get students to make observations from carefully designed demonstrations and see if they can put together their ideas about what is happening, what factors affect what is happening and why it is happening. The sense of achievement in reproducing Faraday's laws will be something that will inspire students to continue looking carefully at physical phenomena to see if they can work out for themselves why things behave the way they do, just like scientists did a long time ago.
- This should now allow students to formalise their observations into Faraday's laws, summed up by the equation: $\varepsilon \propto \Delta(N\Phi)/\Delta t$, where N represents the number of turns of conductor experiencing the change in magnetic flux, Φ represents the product of the magnetic flux density, B, and the perpendicular area, A, through which it acts. (The N in this equation is usually attributed to Neumann, not to Faraday.) If N is considered to be a constant in any arrangement of magnetic field and coil, then students who have already covered the product rule in mathematical differentiation may like to look at how to expand this equation so that they can see a change in magnetic flux is possible through either a change in position (i.e. a movement of some kind), or a change in magnetic flux density, or both. Questions in exams will not expect students to perform calculations that involve both B and A changing.

- Introducing Lenz's law is best done with examples of its effect, see below. The concept of electromagnetic breaking is well used by personal exercise cycles, monorails and several amusement park rides involving falling towards the ground.
- The work on generating electricity using a rotating coil in a magnetic field leads to ideas about alternating currents and root mean square values. You can demonstrate this nicely using a coil that can be rotated inside a uniform magnetic field, with a centre zero galvanometer attached to the end of the coil. Students should observe that changing the frequency of rotation of the coil changes not only the frequency of the induced current, but also the magnitude of it – because the induced emf is proportional to the rate of change of flux.
- If students consider the idea of changing the magnetic flux by changing the magnetic flux density, then they should see that an alternating current in a coil will produce an alternating magnetic flux. This then will allow an induced emf in another coil that experiences this changing flux. This is the principle of the transformer.
- The use of rectification circuits (this is possibly a way to link the section about capacitors with this topic), especially those involving diodes, will show students how to convert between an alternating current and a direct current.
- In the same way as above, students can learn about circuits containing capacitors by making observations from experiments. By taking measurements of current as a function of time, students can draw graphs of current against time to show how the current varies, they can integrate the graphs (by counting up the squares) to find the charge that has flowed, they can examine the time constant idea and they can explore the effect of using different voltage supplies, different resistors and different capacitors.

Practical activities

- A good way to start this topic is to demonstrate the idea that an induced emf will make a current flow in a conductor. With a uniform magnetic field (two opposite poles of magnets placed a small distance apart will produce a uniform field between the poles), a moving wire that is connected to a galvanometer will have induced in it an emf that will make a current flow (because it is a conductor). This current can be displayed by the galvanometer. It is important to guide students into a line of thinking that is something along the lines of: when something changes, such as the position of the wire relative to the magnetic field, then a current occurs in the wire. If nothing changes, such as any motion of the wire or magnet, then no current occurs.

  It is worthwhile at this point to remind students that currents flow because of a potential difference and because there is a conducting path. This should help students to accept that an induced emf will occur if you pass a non-conductor between the poles of the magnets, but because it is a non-conductor, no current will flow.

  Now students can make observations of the various factors that affect the induced emf. These are:

  (i) how fast the wire moves

  (ii) the direction in which the wire moves, students should appreciate that some component of the wire's motion must be perpendicular to the direction of the magnetic field lines

  (iii) the strength of the magnetic field, i.e. its magnetic flux density.

- The amount of wire that is actually moving through the field; this is nicely demonstrated by looping the wire into several turns and passing part of this coil through the field. Students can also observe that if you bend the wire back on itself no current flows. Students should be able to work out why this is happening.

- A good demonstration is to show what happens to a metal plate when you let it move through a magnetic field. You will need a strong magnet (something like 0.1 to 0.4 T would be ideal) and an aluminium plate that has a hole drilled into one corner. If a spindle is placed through the hole, the plate should be free to rotate around the spindle, in fact you only need the plate to be able to swing like a pendulum. It may also be a good idea to shape the plate into a teardrop shape with the spindle passing through the narrow pointed end of the plate.
  Without the magnetic field present, the plate will swing freely, and for some time. When the plate is made to swing between the poles of the magnet, it will stop (or be significantly slowed down) when it passes between the magnet's poles. This is an amazing effect for students to see.
- This eye-catching demonstration is even better shown with a long copper tube (about 2 m long is ideal) and a small cylindrical strong magnet. An object falling about 2 m through the air will take about 0.6 seconds to reach the floor. The magnet will take about **ten times longer** than this if it is dropped through the copper tube. Students will love seeing this.
  It is at this point that students need to find a way of explaining what is happening using sensible physics. There are two ways of going about this:

  (i) Using an energy-based idea. When an induced emf causes a current to flow, the current requires energy. This energy can only come from the kinetic energy of whatever is moving. So kinetic energy is reduced and the moving object slows down. This is the concept of electromagnetic breaking.

  (ii) Lenz's law. If a current is induced in a conductor and the conductor is within a magnetic field, then a catapult field is going to be set up that exerts a force on the conductor. As Lenz's law states that the effect of any induced emf is to oppose the original flux change, the direction of the induced emf is such that the current that flows will create a catapult field to exert a force on the conductor in the opposite direction to the way it is moving, hence slowing down the movement of the conductor, as observed.

  Students will find the energy argument easier to deal with.
- Another nice demonstration is to set up a bar magnet attached to the end of a couple of springs, so that the bar magnet can oscillate vertically. If a coil is placed below the bar magnet and attached to a galvanometer, then when the bar magnet oscillates an oscillating current will be observed in the coil. This may be useful revision of ideas already met.
- Rotating a coil of wire within a magnetic field will produce an alternating current in the coil. This is a good demonstration. Students should consider the two effects of changing the frequency of the rotation: the peak induced current and the frequency of the induced alternating current, both ideas follow on from Faraday's laws. As this is the basis for the production of electricity (i.e. this is what an electrical generator does), students need to be familiar with this.
- Setting up a half-wave rectifier circuit, using one diode, will be the first step to showing students how to convert an alternating current into a direct one. With a bridge of four diodes, full-wave rectification can be demonstrated. Then, for advanced students, it is possible to show the effects of smoothing circuits, although you may have to have covered the work on capacitors beforehand if it is to make sense to students.
- Students should now be ready to investigate the operation of a transformer. You will need a double beam oscilloscope to do this, although an ac voltmeter can be used if one is not available. Wire up a signal generator to the primary coil and to one input of the oscilloscope (or an ac voltmeter) and wire the secondary coil to the other input of the oscilloscope (or ac voltmeter.) Students can then investigate how the voltage on the secondary coil depends on:

  (i) the number of turns on the primary coil

(ii) the number of turns on the secondary coil

(iii) the frequency of the supply to the primary coil

(iv) the voltage across the primary coil.

This should lead to the transformer equation.

- For the investigation of R–C circuits, students need only a battery, ammeter, switch, variable resistor and variable capacitor (or you can use a set of different value resistors and capacitors). If possible try to make the time constant of the circuits the students will use to be something sensible, such as 20 or 30 seconds, so that a charging, or discharging, capacitor will take about 2 or 3 minutes.

  Students should measure the current as a function time for a range of voltage supplies, resistances and capacitances. For each example, students should draw the graph of current against time. Integrating the graph (by hand by counting up the squares or by using a software package to draw the graph that has an integration facility – a nice use of ICT) gives values of how much charge has flowed. Students can then investigate:

  (i) how Q depends on V, a graph of Q against V produces a proportional relationship whose gradient is C, leading to the definition of C. The area under the graph of Q against V gives the energy stored by the capacitor, another important relationship that the students need to learn.

  (ii) how the initial current depends on V and on R.

  (iii) how the time it takes for the current to fall to 37% if its original value depends on R and C, leading to the idea of the time constant of the circuit.

  All of these investigative activities link directly with aim 6 of the group 4 aims in the IB Physics guide.

- If students consider the five features of an R–C circuit: current, voltage across the resistor, voltage across the capacitor, charge on the capacitor plates and energy stored by the capacitor, then it is the relationships between these five quantities that will form the basis of questions that will appear in exams. It is worth finding a good way for students to learn these relationships. A large poster showing visually what these quantities are, how they change during the charging and discharging of an R–C circuit and what their relationship to each other is very useful for students to produce and will provide an excellent summary of the knowledge students have gained from this section of the topic.

- Please see the available practical notes for further ideas.

ICT

- The University of Colorado website has a number of useful simulations to help with Faraday's Laws (http://phet.colorado.edu/en/simulation/faraday and http://phet.colorado.edu/en/simulation/faradays-law).

- Demonstrating the phase difference between the primary and the secondary coils of a transformer can be done nicely with a spreadsheet by drawing two sine waves that are ¼ of a wave out of phase.

- Software packages used by students to plot graphs will be a good use of ICT, particularly if they can integrate graphs. A number of these packages are available, but you may have to pay a large amount for a license to use them in a school or college.

Common problems

- Lenz's law is universally considered to be a difficult concept for students to understand. It is worth spending plenty of time with this. The key idea is that the induced emf will have an effect that tries to prevent the magnetic flux from changing. So if the change in flux is due to something moving, the effect of the induced emf will be to slow down whatever is moving; if the change in flux is due to a changing magnetic field, then the effect of the induced emf will be to produce a magnetic field that acts to prevent the magnetic field from changing. If students are familiar with the concept of negative feedback, they should find this idea easier to cope with.

- Because an induced emf is proportional to the rate of change of flux, this induced emf will be ¼ of a wave out of phase with the current that is causing it. Students find this something that is easily overlooked, so it is worth stressing this, perhaps by drawing graphs that students can differentiate by eye.

Theory of knowledge (TOK)

- This topic is full of specialist language that non-scientists will find very difficult to understand. What problems does this create for scientists in their attempts to communicate with the non-scientific community? To what extent can language be dumbed down for the sake of simplicity before important detail is lost?

International-mindedness

- Although there has not been an internationally agreed value of the rms voltage used by countries for their electrical supply, the use of a 50 Hz frequency does seem to be quite widespread. This cannot be a random result. Governments have been obliged to provide a reliable supply of electricity to their populations.