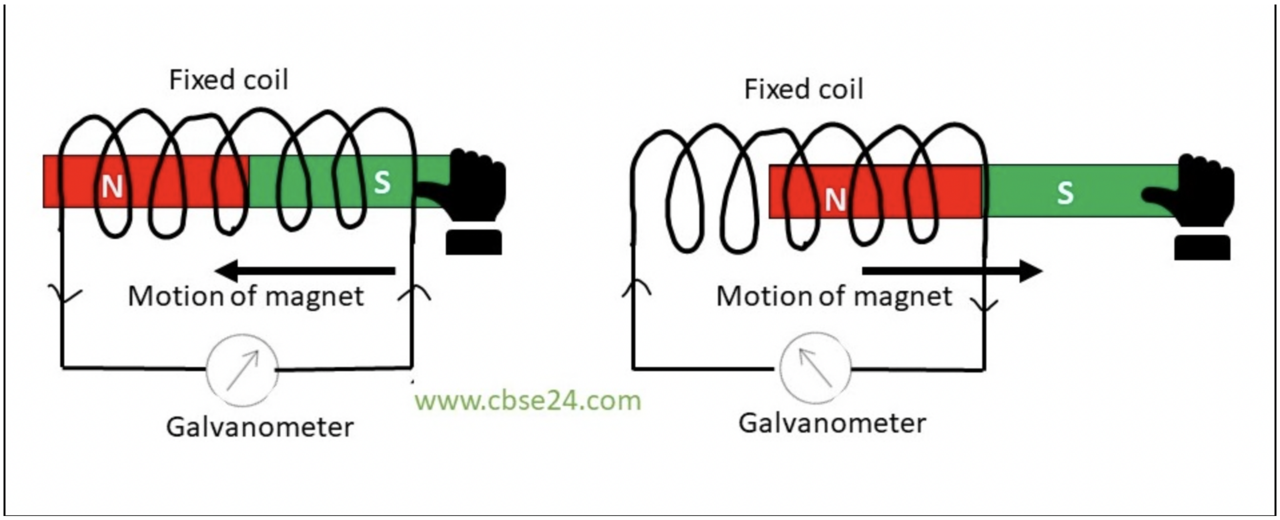
LC Physics: Electromagnetic Induction

1 What is Electromagnetic Induction?

We already discussed the relationship between electric and magnetic fields: recall how a changing magnetic field will 'induce' a current, and how a current will 'induce' a magnetic field. This is called electromagnetic induction, and today, we're going to look into this concept in practice.

1.1 Faraday's Law

Consider a conducting coil connected in series with a galvanometer.



Take a magnet and push it slowly inside the coil. What will you see?

The changing (moving) magnetic field induces a current, which induces an emf, which is detected by the galvanometer.
Pull the magnet slowly out again, what do you see now?

Another emf will be detected, but in the opposite direction!

From this, we can say that relative movement between the coil and the magnet will induce an electric current in the coil. Ergo, we say that **an emf is induced whenever the magnetic flux in a conductor changes**. We call this **electromagnetic induction**.

If you experiment with magnets of different strengths, you will notice that the greater the magnetic flux density, the greater the emf induced. That is to say:

$E \propto B$

If you experiment this time with coils with different numbers of turns, you will notice that the more turns the coil has, the greater the magnetic field induced:

$E \propto N$

You will also find that the faster you move the magnet around (the faster the magnetic field changes relative to the coil), the more current that will be generated:

$E \propto v$

If you combine these three results, you will find one of the most profound discoveries in all of physics: Faraday's Law!

Faraday's Law states that whenever there is a change in the magnetic flux linking a circuit, an emf is induced whose strength is proportional to the rate of change of flux linking the circuit.

1.2 Michael Faraday

Michael Faraday (1791-1867) was one of the most important experimental physicists of all time. Known for his work alongside James Clerk Maxwell to develop Maxwell's Equations, he laid the experimental groundwork for all of electromagnetism. He investigated static electricity, developed the electric motor and electrolysis, and discovered electromagnetic induction. This work is the reason modern electronics are possible.

Where you'll see his name (non-exhaustive list):

- Faraday Cage (remember this?)
- Unit of Capacitance: Farad (F) (We'll cover this in more detail soon)

2 Lenz's Law

Okay, so we have established that a changing magnetic field induces a current in a coil of wire. But what direction will the current flow in? Can we control the direction of current flow?

We can check this experimentally!

Let's connect a coil to a galvanometer, then put a regular bar magnet on a weighing scale. If you move the coil away from the magnet (up), you'll see that the magnet appears to lose weight. Similarly, if you bring the coil down over the magnet, the magnet will appear to get heavier. What's happening?

The emf induced in a coil by a changing magnetic field produces a current flow. BUT, as we've already seen, current induces a magnetic field. This magnetic field opposes the change that caused it. In short, the system turns into two magnets whose like poles are facing eachother.

Lenz's Law states that the direction of the induced emf is always such as to oppose the change causing it.

3 Generators

3.1 Intuition of Lenz's Law

Can you see a link between Lenz's Law and Newton's 3rd Law?

Lenz's Law is the result of the law of conservation of energy. Mechanical energy (moving the magnet) is turned into electrical energy (current). According to Newton's 3rd Law, the magnet in the coil is doing work (exerting a force) and so, must experience an **equal and opposite force**. So, it makes sense that the induced emf will always oppose the change that caused it.

3.2 The Maths of Faraday

Recall: Magnetic flux density (B) is the magnetic flux (Φ) per unit area (A) at right angles to the direction of the magnetic field lines.
$B = \frac{\Psi}{A}$
$\Psi = BA$

This is how the unit of magnetic flux, the Weber, is defined: 1Wb is the magnetic flux that, linking a circuit of one turn, produces in it an emf of one volt as the flux is reduced to zero at a uniform rate in one second.

Now that we have a few more definitions and mathematical tools under our belt, let's return to Faraday's Law. Faraday's Law can be stated mathematically as:

$E = -N\frac{d\Psi}{dt}$

Where E is the emf induced, N is the number of turns in the coil and $-\frac{d\Psi}{dt}$ is the rate of change in magnetic flux with respect to time (the minus sign is due to Lenz's Law: equal and opposite).

Remember earlier, we proved experimentally that induced emf was proportional to magnetic flux density, the number of turns in the coil, and the velocity of the magnet relative to the coil? There's one more proportionality constant: E is also proportional to l, the length of the conductor inside the magnetic field.We can put those together to find yet another expression for Faraday's Law:

$E = -NBlv$

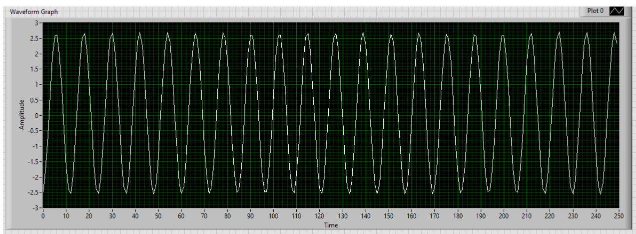
3.3 Right Hand (Generator) Rule

Hold your right hand out with your thumb, forefinger and center finger at right angles.

- Forefinger = direction of field
- Thumb = direction of thrust (movement)
- Center finger = direction of current

3.4 AC Voltages

If we measure voltage versus time of an AC signal, it will look something like this:



Here are some terms we use to talk about AC voltages:

- Peak to Peak voltage: the maximum voltage minus the minimum voltage.
- Peak voltage: the maximum voltage (don't mix it up with peak-to-peak!).
- Root Mean Square (RMS): peak voltage divided by the square root of two.

More on root mean square: if you average the voltage of an AC signal, you will get zero (do you understand why?). Instead, we square all values first, find the average of those, then square root it. The square root reverses the square root of the first step.

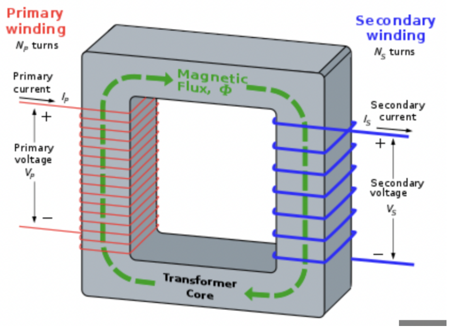
$V_{rms} = \frac{V_0}{\sqrt{2}}$

We can use the same method to find the root mean current:

$I_{rms} = \frac{I_0}{\sqrt{2}}$

Try 5.1!

4 Transformers



A transformer is a device used to change the voltage of AC signals. The primary (input) coil and the secondary (output) coil is wrapped on either side of a soft-iron frame, as in the above image. As an alternating current is passed through the primary coil, a magnetic field is induced. This field is felt by the secondary coil, and in turn induces a current to flow in it.

To quantify this phenomenon, we use the formula:

$\frac{V_1}{V_0} = \frac{N_p}{N_s}$

where V_1 is the voltage in the primary coil, N_p is the number of turns in the primary coil, V_0 is the emf induced in the secondary coil, and N_s.

Try 5.2!

5 Practice Problems

1. The voltage that the ESB supplies to homes, schools, shops ect. is 220V (rms). What is the peak value of this voltage? (Ans: 308V)
2. A transformer has a primary coil of 200 turns and a secondary coil of 20 turns. The primary coil is connected to a 20V AC supply. What EMF is induced in the secondary coil? Is this a step-up or step-down transformer? (Ans: 2V, step-down)