MRSO Exam Prep Course

Module 5

Faraday’s Law of Induction

Section 5.1 Faraday's Law

Faraday’s Law of Induction is the quantitative relationship showing that if we have a changing magnetic field, it will induce a voltage in a circuit. This is the fundamental principle in MRIs.

More specifically, in Faraday’s experiment, he created an energized coil (H’ in Image 5.1). This coil of energized wire created a magnetic field around it. The smaller coil labelled H is not energized, but its wires are connected to a light labelled G. Since this coil is not energized, it cannot supply power to turn on the light. However, the material properties in the coil allow it to act as a magnet. Faraday then placed the larger coil H’ over top of coil H to where coil H was inside of coil H.’ Then, he removed the larger coil and again placed it back on the small coil. This created a changing magnetic field, which induced a current in the wires of coil H. The current produced in the coils provided electricity to turn on the light labelled G.

In the case of Faraday’s experiment, if you move the coils faster (closer and farther away), the voltage will be increased. Also, the closer the conductive object is to the magnetic field, the more voltage will be generated.

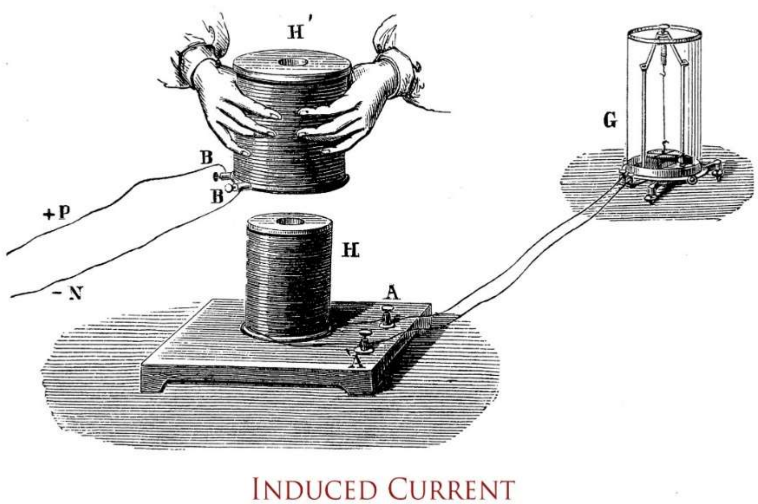

Image 5.1

Another example is shown in this video. This video shows Faraday inserting a magnet inside a coil. This coil is connected to another coil of wires over the top of a compass. As Faraday places the magnet inside the coil, the result is that the compass begins to move. So, what is happening here? When the magnet is introduced and removed from the coil, it creates a changing magnetic field. This process induces a current in the coil. This coil travels through the copper wire and travels through the copper coil over the compass. This current over the compass then induces a magnetic field that manipulates the compass.

5.1.1 Eddy Currents

As part of Faraday's Law, it was also discovered that when you have changing magnetic fields in the conductor, loops of electrical currents will be induced on the electrical conductor. These swirls of electrical energy are called Eddy currents. These currents are unwanted because:

1. They generate their magnetic field, slightly distorting our MRI image or producing artifacts in our image.
2. They produce unwanted heat, which may transfer to our patient.

Eddy currents do not provide images but only produce local signals in a difficult-to-understand measurement plane—the buildup of a responding electromagnetic field will interfere with the exciting field. In Image 5.2 the absolute probe shows a magnetic field that is not manipulated by an electric field, and the differential probe shows what happens when an electric field (Eddy currents) comes into play. This electric current will have a positive charge and a negative charge, which distorts the image.

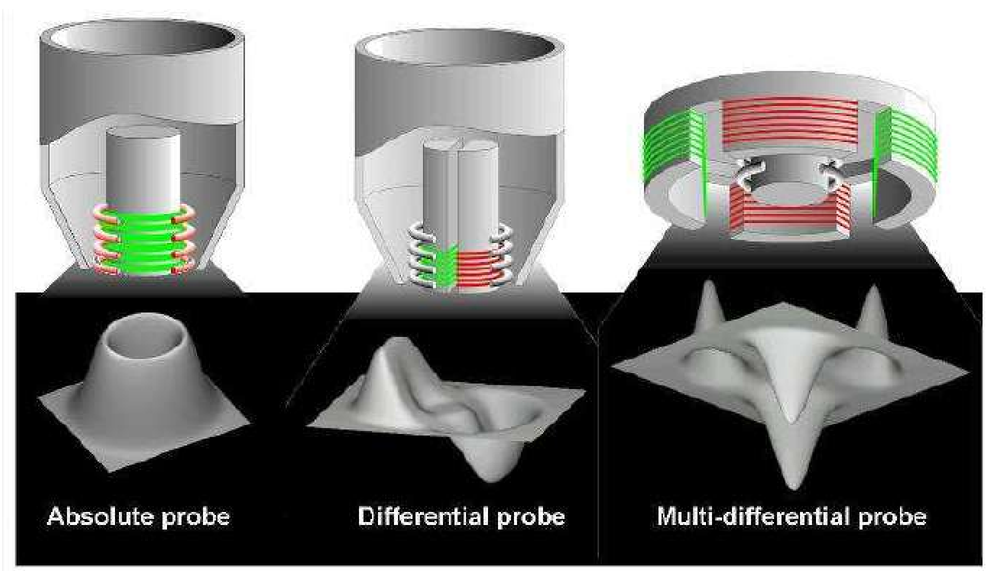

Image 5.2

Mook, Gerhard & Michel, Fritz & Simonin, Jouri. (2022). Electromagnetic Imaging Using Probe Arrays. Strojniški vestnik – Journal of Mechanical Engineering. 2011. 10.5545/sv-jme.2010.173.

Depending on the magnetic field's direction, the Eddy currents' swirling may run clockwise or counterclockwise. Using the right-hand palm rule (Image 5.3), you can determine the direction of the magnetic field and the current. To do this, point your fingers of your right hand in the direction of the magnetic field. In this case, your fingers point into the page, your palm points to the left, and your thumb will point up. Your thumb indicates the direction of the current. Visualize the Eddy currents swirling around in a circular motion, representing the current flow.

When your thumb is pointing upward, this would indicate that the current flows counterclockwise within the circle.

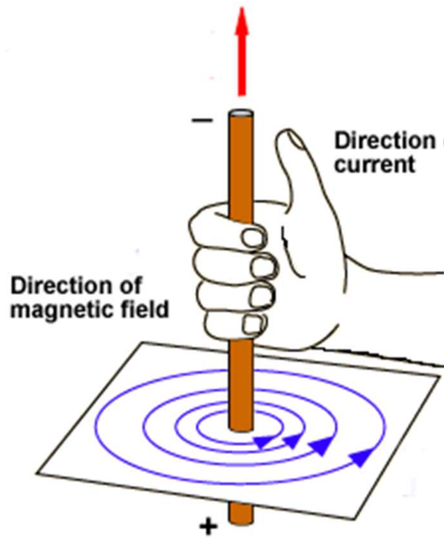

Image 5.3

Section 5.2 Lenz's Law

As a reflection of Faraday's Law of Induction, Lenz's Law is important to understand. Lenz's Law states that the direction of the current induced in a conductor by a changing magnetic field is such that the magnetic field *created by* the induced current opposes the initial magnetic field. To understand this better, let's look more into detail of Faraday's Law of Induction:

$$\boxed{\mathcal{E} = -N\frac{\Delta\phi_M}{\Delta t}}$$

Faraday's Law

N= number of loops
øM= change in magnetic flux
Δt= change in time
Ɛ= induced voltage (also known as emf)

Image 5.4

If we look at the formula in Image 5.4, a voltage Ɛ is induced in a coil due to the rate of change in the magnetic flux ($\Delta\Phi/\Delta t$). The number of loops "N" in the coil also affects the voltage. We can see that an increase in the number of loops produces a higher induced voltage.

Lenz's Law was developed after analyzing and understanding the negative sign in this equation. The negative sign shows that the direction of the induced current is such that the generated magnetic field will oppose the change in the magnetic flux to which it owes its existence. Consider, for a moment, that this was not the case. In other words, if electric currents are created from magnetic currents, and those magnetic currents create more electric currents which are *unopposed*, we would ultimately see an infinite increase in compounding energy. The negative sign in Faraday's Law shows that energy transfer obeys the law of energy conservation: A system cannot produce more energy than it initially has.

The difference between Lenz's Law and Faraday's Law is that Lenz's Law is about the conservation of energy applied to electromagnetic induction, and Faraday's Law is about the electromagnetic force produced.

With these two laws discussed, we can now utilize Faraday's Law to determine how much current is produced with an induced magnetic flux, and with Lenz's Law, we can now determine the direction of the induced current. Image 5.5 is another example of using the right-hand rule to determine the direction of the current.

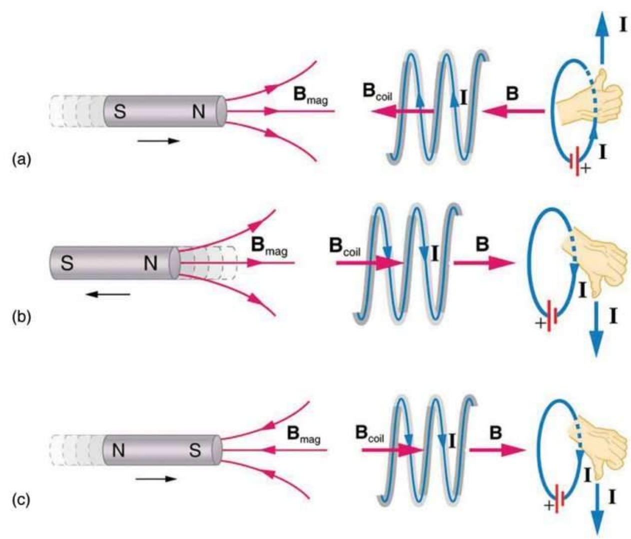

Image 5.5

5.2.1 Lenz's Force

Lenz's Force is a type of opposing force that is generated by a magnetic field in an object. When we discuss Lenz's force in the context of MR safety, we are referring to electrically conductive materials that come near the magnetic field. As per Faraday's Law, electrically conductive objects can produce electrical currents in a magnetic field. Moreover, we also know that the more rapidly the magnetic field changes, the more electrical current will be generated.

When a patient has an electrically conductive implant, the implant can react to the external magnetic field's influence by moving itself. This happens because the implant is electrically conductive.

When it comes to implants, removing electrically conductive material is impossible, just like we cannot eliminate the fringe field emanating from the primary magnet. However, we can take steps to lower the likelihood of implant reactions to the fringe field. By remembering Faraday's Law, we know that the faster we move a magnetic field through a conductive material, the more current it produces. Conversely, moving a conductive material through a magnetic field generates more movement, also known as Lenz's Force (Image 5.6). To reduce the risk of Lenz's Force, we can slow down our movement when approaching the MRI.

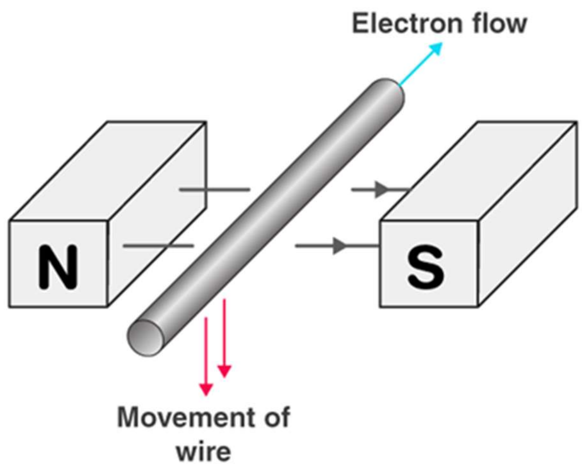

Image 5.6