10.1: Introduction to Electromagnetic Induction

In 1820, Oersted had shown that an electric current generates a magnetic field. But can a magnetic field generate an electric current? This was answered almost simultaneously and independently in 1831 by Joseph Henry in the United States and Michael Faraday in Great Britain. Faraday constructed an iron ring, about six inches in diameter. He wound two coils of wire tightly around the ring; one coil around one half (semicircle) of the ring, and the second coil around the second half of the ring. The two coils were not connected to one another other than by sharing the same iron core. One coil (which I'll refer to as the "primary" coil) was connected to a battery; the other coil (which I'll refer to as the "secondary" coil) was connected to a galvanometer. When the battery was connected to the primary coil a current, of course, flowed through the primary coil. This current generated a magnetic field throughout the iron core, so that there was a magnetic field inside each of the two coils. As long as the current in the primary coil remained constant, there was no current in the secondary coil. What Faraday observed was that at the instant when the battery was connected to the primary, and during that brief moment when the current in the primary was rising from zero, a current momentarily flowed in the secondary – but only while the current in the primary was changing. When the battery was disconnected, and during the brief moment when the primary current was falling to zero, again a current flowed in the secondary (but in the opposite direction to previously). Of course, while the primary current was changing, the magnetic field in the iron core was changing, and Faraday recognized that a current was generated in the secondary while the magnetic flux through it was changing. The strength of the current depended on the resistance of the secondary, so it is perhaps more fundamental to note that when the magnetic flux through a circuit changes, an electromotive force (EMF) is generated in the circuit, and the faster the flux changes, the greater the induced EMF. Quantitative measurements have long established that:

While the magnetic flux through a circuit is changing, an EMF is generated in the circuit which is equal to the rate of change of magnetic flux \( \dot{\Phi}_B \) through the circuit.

This is generally called "Faraday's Law of Electromagnetic Induction". A complete statement of the laws of electromagnetic
induction must also tell us the direction of the induced EMF, and this is generally given in a second statement usually known as "Lenz's Law of Electromagnetic Induction", which we shall describe in Section 10.2. When asked, therefore, for the laws of electromagnetic induction, both laws must be given: Faraday's, which deals with the magnitude of the EMF, and Lenz's, which deals with its direction.

You will note that the statement of Faraday's Law given above, says that the induced EMF is not merely "proportional" to the rate of change of magnetic B-flux, but is equal to it. You will therefore want to refer to the dimensions of electromotive force (SI unit: volt) and of (B)-flux (SI unit: weber) and verify that \( \dot{\Phi}_B \) is indeed dimensionally similar to EMF. This alone does not tell you the constant of proportionality between the induced EMF and \( \dot{\Phi}_B \), though the constant is in fact unity, as stated in Faraday's law. You may then ask: Is this value of 1 for the constant of proportionality between the EMF and \( \dot{\Phi}_B \) an experimental value (and, if so, how close to 1 is it, and what is its currently determined best value), or is it expected theoretically to be exactly 1? Well, I suppose it has to be admitted that physics is an experimental science, so that from that point of view the constant has to be determined experimentally. But I shall advance an argument shortly to show not only that you would expect it to be exactly 1, but that the very phenomenon of electromagnetic induction is only to be expected from what we already knew (before embarking upon this chapter) about electricity and magnetism.

Incidentally, we recall that the SI unit for \( \Phi_B \) is the weber (\( \text{Wb} \)). To some, this is not a very familiar unit and some therefore prefer to express \( \Phi_B \) in \( \text{T m}^2 \). Yet again, consideration of Faraday's law tells us that a perfectly legitimate SI unit (which many prefer) for \( \Phi_B \) is \( \text{V s} \).

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