

6. Electromagnetic Induction

Module 2 : Lenz's Law and Eddy Currents

This module is designed to help you to:

- explain Lenz's law;
- apply the concept of Lenz's law to find the direction of induced emf;
- use Fleming's left hand rule to predict the direction of force on a current carrying conductor;
- use Fleming's right hand rule to predict the direction of induced emf /current;
- illustrate and apply Ampere's right hand screw rule;
- explain the phenomenon of eddy currents and demonstrate the same through simple experiments;
- analyze the application of eddy currents.

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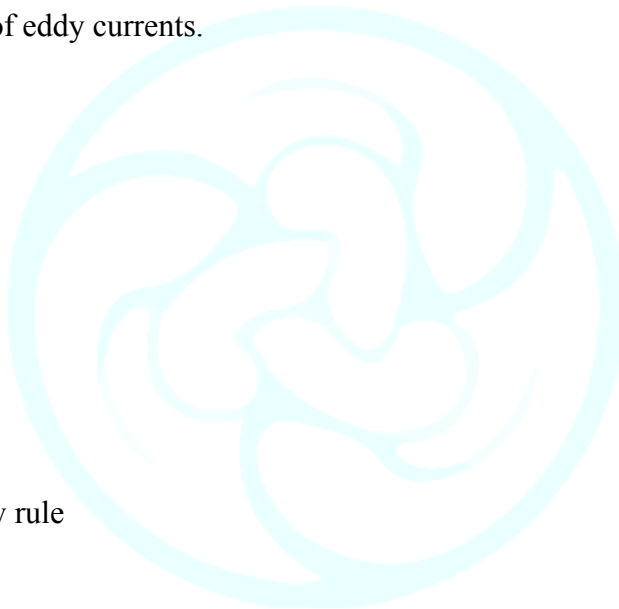
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6.2.1 Introduction

In the previous Module of this unit we developed the concept of flux, magnetic flux, electromagnetic induction and Faraday laws and applied those concepts to solve problems. In this module we will discuss Lenz's law which is used to find the direction of current induced due to electromagnetic induction. We will also discuss Fleming's left hand and Fleming's right hand rule. At the end of this module we will discuss eddy currents and their applications in daily life.

6.2.2 Lenz's law

This law tells about the polarity of induced emf due to a change in magnetic flux linked with a coil. The minus sign in Faraday's law of electromagnetic induction is based on this law. Lenz's law can be stated as - "the polarity of induced emf is such that it tends to produce a current which opposes the change in magnetic flux that produced it."

Now, observe Fig 6.2.1 carefully. In (a) the N-pole of the bar magnet is approaching the coil. The direction of the current induced in the coil will be such that it opposes the approaching N-pole. So the plane of the coil facing the approaching N-pole will have north polarity so that the approach of the N-pole of the magnet can be opposed. Hence, the direction of flow of current will be anticlockwise.

Following the above logic one can ascertain the direction of the induced current in case (b) to be clockwise.

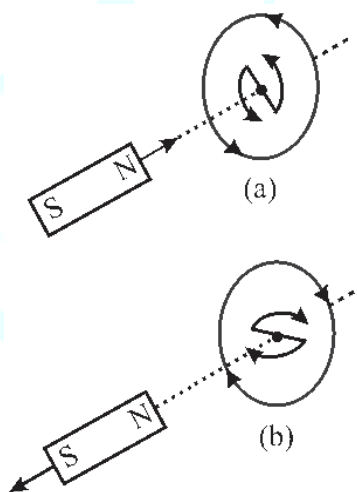


Fig. 6.2.1 Pictorial demonstration of Lenz's rule

Activity 6.2.1 This simple activity, done with the help of a toy motor, gives a vivid illustration of Lenz's law. Take a toy motor with (tiny) fan blades attached to its axle. Keeping the terminals of the motor in the open condition, give the fan blades a rotation with the hands and let them rotate. It would be observed that the fan blades keep on rotating for quite some-time. Now short the two terminals of the motor and again give the fan blades a similar rotation with the hands. What do we observe now? The fan-blades come to rest in practically no-time. Why this difference? What is the reason for the difference in the two cases? When the motor terminals are left open, the induced emf, set up due to its rotation, does not produce any induced current. However, when the motor terminals are shorted, there is a large induced current, which, as per Lenz's law, opposes the cause (the rotation given to the axle by the hands) that had produced it. Hence, it provides a damping effect which quickly brings the fan blades to rest.

We now talk of some simple rules to illustrate how to find the direction of the induced current.

6.2.3 Fleming's left hand rule

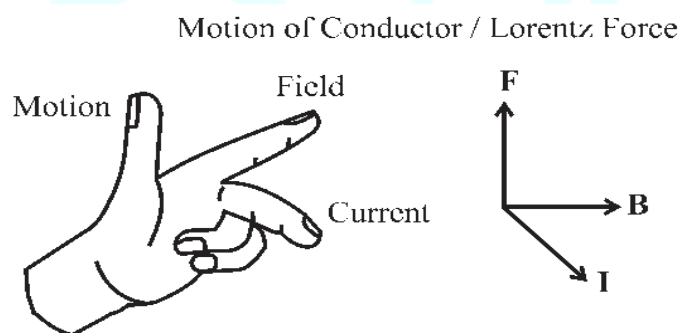


Fig. 6.2.2 Demonstration of Fleming's left hand rule

By using this rule, we can find the direction of force acting on a current carrying conductor placed in an external magnetic field.

Refer to Fig. 6.2.2. If we fold the fingers of our left hand as shown in Fig. 6.2.2 then, if the index finger points in the direction of the magnetic field, the middle finger points in the direction of current then the thumb will show the direction of force acting on the conductor or the direction of motion of the conductor.

This rule may be used in explaining the working of electric motors.

6.2.4 Fleming's right hand rule

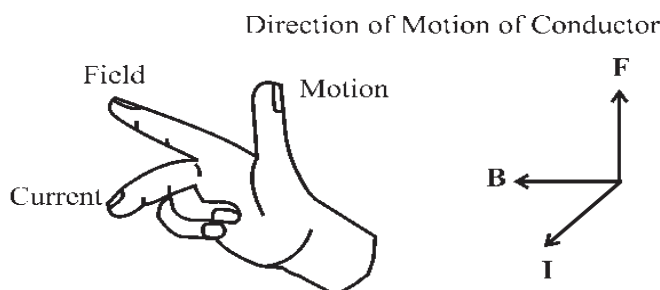


Fig. 6.2.3 *Demonstration of Fleming's right hand rule*

By using this rule, we can find the direction of induced current in a conductor when a conductor moves in an external magnetic field.

Refer to Fig. 6.2.3. If we fold the fingers of our right hand as shown in the figure then, if index finger points in the direction of magnetic field, thumb points in the direction of motion of the conductor, then the middle finger will show the direction of current induced in the conductor.

This rule may be used in explaining the working of electric generators. Question arises, when is Fleming's left hand rule used and when is Fleming's right hand rule used?

Explanation

Though the two rules may appear similar in terms of giving the direction of motion of the conductor (or force), the magnetic field and the electric current, the two rules are used for explaining the working of two different types of devices. The left hand rule is used to explain the working of motors while the right hand rule is used for explaining the working of generators. The reason for using these two different rules for these two types of devices is that the cause and effect of the quantities associated with the motor and generator are different.

In the case of motors the electric current and magnetic field already exist (hence they can be classified as causes) and they are responsible for generating the force which causes the motion in the motor. Thus the force/motion can be treated as the effect.

In case of generators the motion/force and the magnetic field already exists (hence can be classified as the cause) and this motion/force and the change in magnetic field causes the current to be induced or generated. Thus the induced/generated current is classified as the effect.

We can do without these two rules if we take appropriate vector equations and find directions using the right hand screw rule.

$$\mathbf{F} = I(\mathbf{l} \times \mathbf{B})$$

$$\mathbf{E} = \mathbf{v} \times \mathbf{B}$$

Let us now study another rule.

6.2.5 Ampere's right hand screw rule

This rule relates the direction of electric current I to the direction of magnetic field $\mathbf{B}$ due to this current. There are two forms of this rule depending on the geometry of the conductor in which the current is flowing.

Form (i): For an electric current passing through a solenoid or a coil, the direction of magnetic field is given by the right hand thumb when the fingers of right hand are folded in a manner to wrap around the coil or solenoid in the direction of the conventional current [Fig. 6.2.4 (a)].

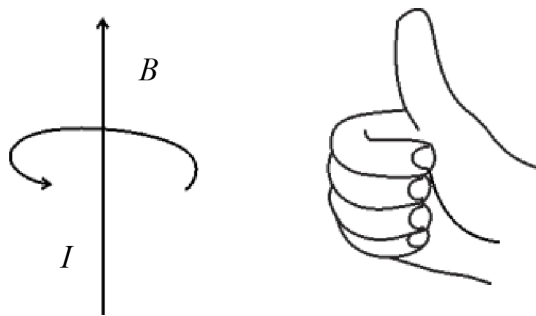


Fig. 6.2.4 (a) *Ampere's right hand rule (when the direction of magnetic field is given)*

Form (ii): For an electric current passing through a straight wire with the right hand thumb pointing in the direction of the conventional current (from the positive to the negative), then the fingers of the right hand curl to give the direction of the magnetic field [Fig 6.2.4 (b)].

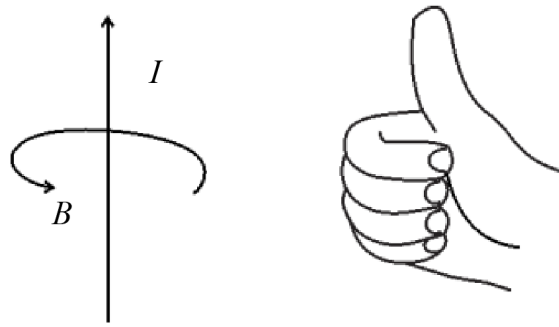


Fig. 6.2.4(b) *Ampere's right hand rule (when the direction of current is given)*

Example 6.2.1 Refer to Fig. 6.2.5. It shows planar loops, of different shapes, moving out of, or into, a region of a magnetic field which is directed normally to the plane of the loop, away from the reader. Determine the direction of induced current in each loop using Lenz's law.

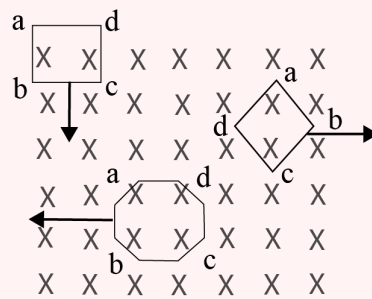


Fig. 6.2.5

Solution In case (1) the magnetic flux through the square loop is increasing, due to the motion of the loop into the region of the magnetic field. The induced current must, therefore, flow along the path $abcd$ so that the magnetic field due to it, opposes this increase in flux.

In case (2), initially the magnetic flux through the rhombus shaped loop remains unchanged until its first end c starts coming out of the magnetic field region. Therefore initially there will be no induced current but as the loop starts coming out of the magnetic field region then due to the outward motion, the magnetic flux through the rhombus loop $abcd$ will start decreasing and there will be an induced current which will flow along $(abcd)$, so that the magnetic field, due to it, opposes this decrease in flux.

As the magnetic flux decreases due to motion of the octagonal shaped loop $abcd$, moving out of the region of the magnetic field, the induced current flows along the $cbadc$. It does so to oppose this decrease in flux.

Note that there are no induced currents as long as the (moving) loops remain completely inside or outside the region of a (uniform) magnetic field. This is because the total magnetic flux, linked with the loop, does not change during such movements.

Explanation

When the square shaped loop ($abcd$) is moved in the direction shown, the area of the loop inside the magnetic field increases. This results in an increase in the magnetic flux linked with the loop, causing an induced current to flow through the loop. According to Lenz's rule, the magnetic field of the induced current must oppose the increase in magnetic flux that produces it. Therefore, the direction of the magnetic field, due to this induced current, should be directed out of the paper toward the reader. By using the right hand thumb rule, we find that the direction of the induced current should be anticlockwise ($abcda$).

When the loop in the second case is moved (gradually) in the direction shown, the area of the loop in the magnetic field, and hence the magnetic flux, (initially) remains unchanged. Therefore, no current will be induced until it begins to move out of the field. Once it begins to move out, an induced current, along the direction $abcd$ would be set up in it. The direction of the induced magnetic field will be along the original magnetic field.

When the loop, in the third case, is moved in the direction shown, the area of the loop inside the magnetic field decreases. The induced current should, therefore, produce a magnetic field that opposes this decrease. Hence, as per the right hand thumb rule, its direction should be clockwise ($cbadc$). Here also the direction of the induced magnetic field will be along the direction of the original field.



Let Us Reflect

Q.6.2.1 Consider a magnet surrounded by a wire with an on/off switch S (Fig. 6.2.6). If the switch is thrown from the 'off' position (open circuit) to the 'on' position (closed circuit), will a current flow in the circuit? Explain.

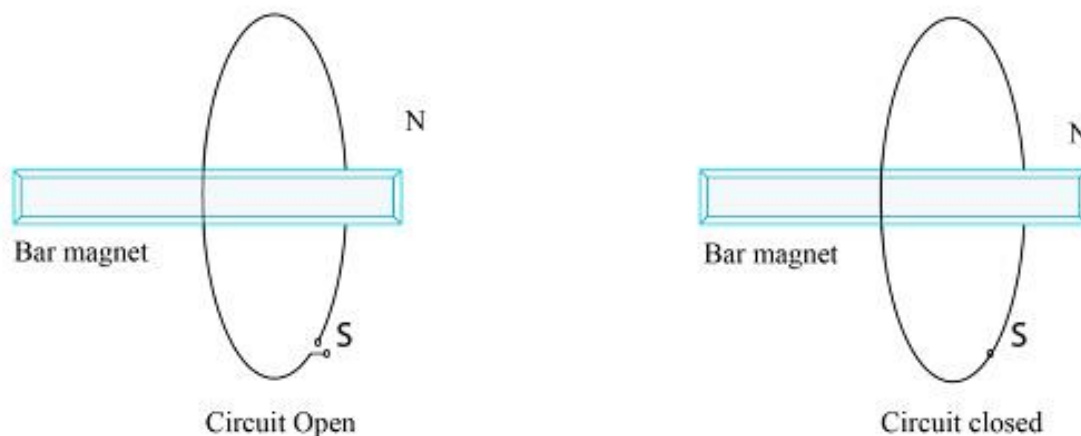


Fig. 6.2.6

Q.6.2.2 A wire, in the form of a tightly wound solenoid connected to a DC source, carries a current. If the coil is stretched so that there are gaps between successive elements of the spiral coil, will the current tend to increase or decrease? Explain.

Q.6.2.3 Consider a metal ring kept on top of a fixed solenoid (say on a cardboard) as shown in Fig.6.2.7. The centre of the ring lies on the axis of the solenoid. If the current is suddenly switched on, the metal ring jumps up. Explain why?

Q.6.2.4 Consider a metal ring kept (supported by a cardboard) on top of a fixed solenoid carrying a current I . The centre of the ring lies on the axis of the solenoid. If the current in the solenoid is switched off, what will happen to the ring?



A.6.2.1 The magnet does not move, nor does the coil. So there is no change of flux through the coil after S is closed. Hence, no emf will be induced and no current will flow.

A.6.2.2 The number of turns per unit length of the solenoid coil decreases, so the magnetic field decreases and thus the flux decreases. Hence, instantaneously an emf will be induced and it would oppose the cause, that is the decrease of the magnetic field. So, instantaneously there will be a tendency to increase the field which can happen by way of an increase of current. So there will be a tendency towards an increase of current.

A.6.2.3 When there is no current, the magnetic field of the solenoid is nil. On switching on the current, there will be an onset of a magnetic field in the solenoid. This change of magnetic field, from zero to non-zero, hence that of magnetic flux, will lead to an induced emf and current in the metal ring. The cause behind this will be opposed. Now the top end of the solenoid as a magnet will have a polarity. And the equivalent magnet corresponding to the induced current in the metal ring will also have its polarities. Now, if the polarity of the top end of the solenoid is N, its formation is equivalent to the momentary advancement of the N-pole towards the ring. So the direction of the induced current in the metal ring will be such that the corresponding magnet will have its polarities oriented towards opposing the so-called advancement of the N-pole. So a N-pole will be created on the lower side of the ring to trigger a repulsion and due to this momentary repulsion, the ring will jump up.

A.6.2.4 If the current is ON in the solenoid, the ring will initially be levitating. This is because of the repulsion between the solenoid's magnetic field and the magnetic field produced by the ring due to induced current. When the solenoid field is switched off, the ring falls down as there is no repulsion anymore.

6.2.6 Eddy currents

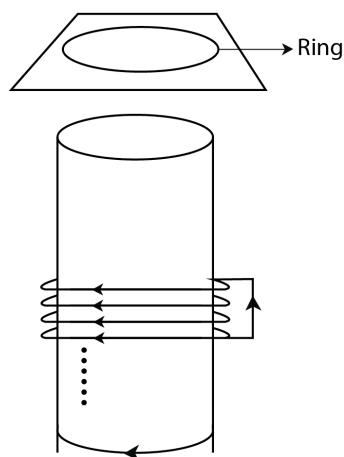


Fig. 6.2.7 A metal ring kept on the top of a solenoid

In order to understand the concept of eddy currents let us do an activity.

Activity 6.2.2

Refer to Fig 6.2.8. Suspend a strong cylindrical/bar magnet from a laboratory stand. Take a thick metal plate of aluminum or copper (of size approximately $6\text{ cm} \times 6\text{ cm}$), you can verify that the magnet does not attract this aluminum or copper plate. Oscillate the magnet like a simple pendulum, without putting the metal plate under it.

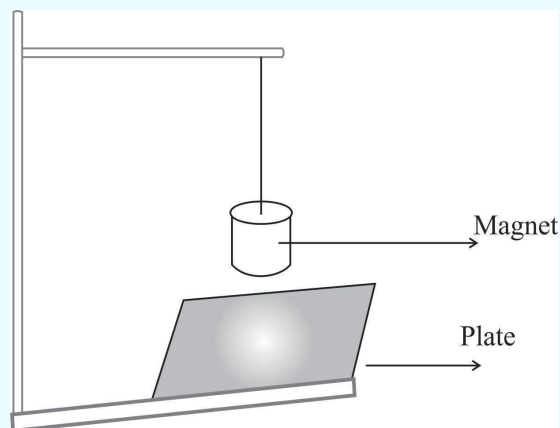


Fig. 6.2.8

Observe the oscillations. Now put the metal plate just below the mean position of the magnet. Again oscillate the magnet and observe the difference. Now the magnet comes to rest much more quickly. This happened due to the production of eddy currents in the metal plate. Such eddy currents are the basis of electromagnetic braking in trains and of the dead-beat action in ordinary laboratory galvanometers.

[**Note:** A neodymium magnet and thick copper plate should be used, if possible].

We now know that an emf is induced in a conductor when it is kept in any changing magnetic field.

Till now we have generally considered the conductors to be in the form of a wire that has been wrapped as a coil. However, the conductor may not always be in the shape of a coil and may not even be a wire. It could be a piece of a flat copper or aluminum plate, or it can be any other conducting object. The only requirement is that the object must be able to conduct electrical currents.

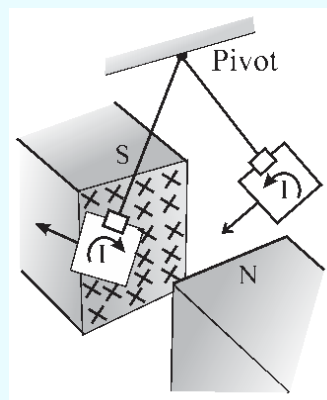


Fig. 6.2.9

When current is induced in a conductor, such as the square piece of metal shown above, the induced current often flows along small closed loops. These induced currents are strongest at the surface but they also penetrate a short distance into the material. These current flow in patterns, in a way, resemble the eddies in a stream. Because of this (presumed) resemblance, the induced currents, in conductors of any arbitrary shape, were named eddy currents.

6.2.7 Applications of eddy currents

Eddy currents, generally regarded only as a cause of loss of energy, do find many useful applications. Besides being used for braking action in trains, electromagnetic damping in several sensitive instruments, and in electric power meters, they are now a part of a device that is a part of several kitchens. The induction cooker works on the basis of eddy currents. The heat produced, through eddy currents, in these cookers, is put to use for cooking, and other heating applications, in and around the kitchen.



Q.6.2.5 Consider a metallic (non-ferromagnetic) pipe with an inner radius of 1 cm. If a cylindrical bar magnet, of radius 0.8 cm, is dropped through the pipe, it takes more time to come down than the time taken by a similar non magnetised cylindrical iron bar dropped through a similar metallic pipe. Explain the reason for this difference.



A.6.2.5 The radius of the cylindrical bar magnet is less than that of the pipe and so it falls vertically through the pipe. Hence the number of field lines emanating from the magnet embracing the metallic paths and through the pipe would change and emf will be induced leading to formation of eddy currents which will oppose the motion of the magnet and thus it would get slowed down. The same does not happen with the iron rod which is a non-magnet.

We shall now study the quantification of electromagnetic induction in the next Module which will be done through the introduction of two terms mutual and self-inductance.

6.2.8 Summary

- Lenz's law states that induced emf opposes the change that produces it. This law can always be used to find the direction of current induced in a coil due to electromagnetic induction.
- Fleming's left hand rule can be used to find the direction of the magnetic force on a current carrying conductor placed in a magnetic field.
- Fleming's right hand rule can be applied to find the direction of the emf /current induced in a conductor moving in a magnetic field.
- If we hold a current carrying conductor in our right hand and keep the thumb in the direction of conventional current then the curl of fingers gives us the direction of the magnetic field.
- If the fingers of the right hand are folded in a manner to wrap around the current carrying coil or solenoid in the direction of the conventional current then the thumb points in the direction of the magnetic field.
- Eddy currents are the currents induced in the body of a conductor of any shape due to changes in magnetic flux linked with it.
- Eddy currents have many applications in our daily life like electromagnetic damping, brakes of trains, speedometers of vehicles, induction furnaces, induction cookers, etc.

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