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Electricity, Magnetism & Optics

Electromagnetic Induction

by
Muhammad Hafiz bin Mazwir
Faculty of Industrial Sciences & Technology
muhammadhafiz@ump.edu.my

Chapter Description

- Aims

  Students will understand Faraday’s law of electromagnetic induction and Lenz’s law

- Expected Outcomes
  - ➢ Able to relate the induced emf in a loop to the change in magnetic flux through the loop (Faraday’s law)
  - ➢ Able to calculate the emf induced in a conductor moving through any magnetic field
  - ➢ Able to determine the direction of induced emf using both Faraday’s and Lenz’s law

Content

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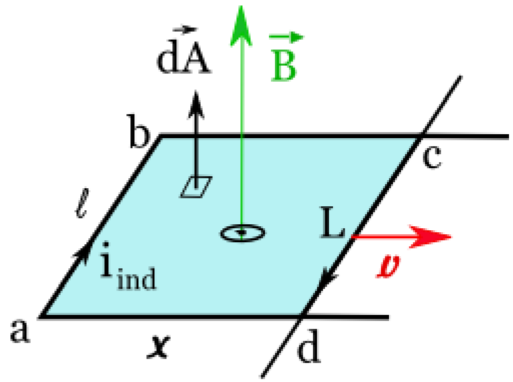
9.3 Lenz's law



Source: Livinus, Wikimedia Commons

9.1 Magnetic Flux

- The magnetic flux, Φ_B through a surface can be defined just like electric flux Φ_E

- The surface is divided into infinitesimally small area $d\vec{\boldsymbol{A}}$ first.
- For each *dA*, the component of the magnetic field perpendicular to the area, $B_\perp$ is determined, and that is $B_\perp = B\cos\phi$, where ϕ is the angle between the direction of $\vec{\boldsymbol{B}}$ and a line perpendicular to the surface

$$\Phi_B = \int \vec{\boldsymbol{B}} \cdot d\vec{\boldsymbol{A}} = \int B\cos\phi \; dA$$

(magnetic flux through a surface)

Magnetic Flux: Uniform field

- Magnetic flux is a *scalar* quantity.
- If $\vec{B}$ is uniform over a plane surface with total area *A*, the equation can be simplified into

$$\Phi_B = B_\perp A = BA\cos\phi$$ (magnetic flux for a uniform magnetic field)

- The SI unit for magnetic flux is **Weber** (Wb)
- $1\ \text{Wb} = 1\ \text{T}\cdot\text{m}^2 = 1\ \text{N}\cdot\text{m/A}$
- Sometimes, $\vec{B}$ is called magnetic flux density

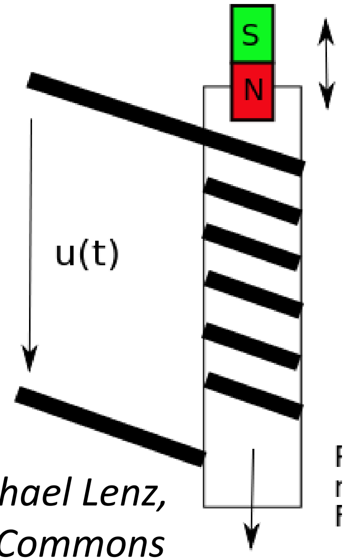
- In Gauss's law, the total *electric flux through a closed surface* is proportional to the total electric charge enclosed by the surface.
- But for magnetism, since there are no such thing as magnetic monopoles, the **total magnetic flux through any closed surface must be zero!**

$$\oint \vec{B}\cdot d\vec{A} = 0$$ (magnetic flux through any closed surface) (Gauss's law for magnetism)

9.2 Faraday's Law

- Moving electric charge and current can produce magnetic fields
- So, can magnetic field create current??
- These are what Michael Faraday and Joseph Henry thought of in 1830s

- Faradays designed an experiment where a coil of wire connected to a galvanometer is placed between the poles of an electromagnet. He then changed the variables such as switching off the magnet, or made the wire loop smaller and larger.



Source: Michael Lenz, Wikimedia Commons

Faraday's experiment result

Coil	Electromagnet	Galvanometer	Changes	
			Magnetic field	Surface area
No current	-	No reading	-	-
Current increase	-	Momentary reading	✓	-
Steady current	-	No reading	-	-
Squeezed	-	Momentary reading	-	✓
Rotated	-	Momentary reading	-	✓
Moved around	-	Momentary reading	-	✓
Decrease loop number	-	Momentary reading	✓	-
-	Turned off	Momentary reading	✓	-
*Any of the above, **reversed***	**-**	***Reversed reading***	✓	✓
*Any of the above, **faster***	**-**	***Higher reading***	✓	✓

Faraday's law

- The common element in the experiment is *changing magnetic flux* Φ_B through the coil connected to the galvanometer.
- In each case, the flux changes either because the magnetic field changes or because the coil is moving through a nonuniform magnetic field.

- Faraday's law of induction states that the induced emf is proportional to the ***rate of change*** of magnetic flux through the coil. And the direction of the induced emf depends on whether the ***flux is increasing or decreasing***.

$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

(Faraday's law of induction with *N* loops)

Direction of Induced emf (Faraday's law)

1. Define the positive direction for the given vector area, $\vec{A}$
2. From directions of $\vec{A}$ and $\vec{B}$, determine the sign of the magnetic flux Φ_B and its rate of change, $d\Phi_B/dt$
3. Determine the sign of the induced emf using Faraday's law. E.g: If the flux is increasing, $d\Phi_B/dt$ is positive, the sign of the induced emf will be negative
4. Finally, determine the direction of the induced emf or current using your right hand. Curl the fingers of your right hand around vector $\vec{A}$ with your right thumb n the positive direction of $\vec{A}$. If the induced emf or current is negative, it is in the opposite direction as your curled fingers (and vice versa)

9.3 Lenz's law

- Another way of determining direction of an induced current or emf.
- Lenz's law is an easier method to use

Lenz's Law

The direction of any magnetic induction effect is such as to oppose the cause of the effect

- The "cause" may be

1. changing flux through a stationary circuit due to a varying magnetic field OR
2. changing flux due to motion of the conductors that make up the circuit, OR
3. any combination of both.

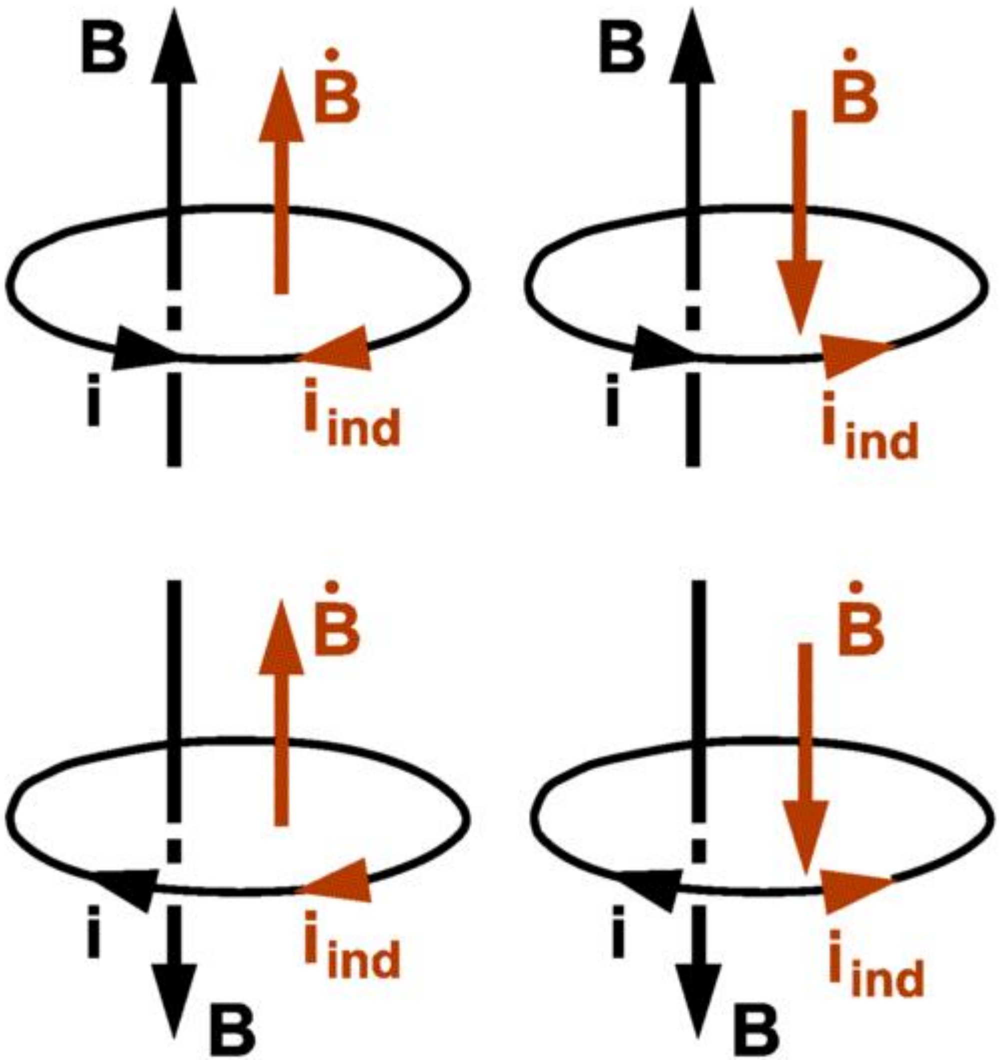
Determining the direction of Induced emf (Lenz's law)

1. Determine whether the magnetic flux is increasing, decreasing, or unchanging.
2. The magnetic field due to the induced current points in the opposite direction to the original field if the flux is increasing; in the same direction if it is decreasing; and is zero if the flux is not changing.
3. Use the right-hand rule to determine the direction of the current.
4. Remember that the external field and the field due to the induced current are different.

Determining the direction of Induced emf (Lenz's law)

Motion of magnet causes increasing upward flux. Induced current is clockwise

Motion of magnet causes decreasing upward flux. Induced current is anti clockwise



Motion of magnet causes decreasing downward flux. Induced current is clockwise

Motion of magnet causes increasing downward flux. Induced current is anti clockwise

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Conclusion

- Faraday's Law
  - The induced emf in a closed loop equals the negative of the time rate of change of magnetic flux through the loop
- Lenz's Law
  - The direction of any magnetic induction effect is such as to oppose the cause of the effect

References

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Thank you!

Next chapter: Inductance

Authors Information

Muhammad Hafiz bin Mazwir
Siti Aisah binti Harun

Material Technology Programme,
Faculty of Industrial Sciences & Technology
Universiti Malaysia Pahang