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INTRODUCTION

- In many ways, the inductor is the dual of the capacitor; that is, the voltage of one is applicable to the current of the other, and vice versa.
- Like the capacitor, the inductor exhibits its true characteristics only when a change in voltage or current is made in the network.
TERMS AND DEFINITIONS

- **Inductor**- a device (usually a coil) that introduces inductance into an electrical circuit.

- **Inductance**- the property of an electric circuit when a varying current induces an electromotive force (EMF) in that circuit or another circuit.

- **Self-inductance**- the property of an electric circuit when an EMF is induced back into itself by a change of circuit current.

- **Henry**- the unit of inductance.
TERMS AND DEFINITIONS

- **Permeability**: the measure of the ease with which material will pass lines of flux.

- **Mutual inductance**: the property of two circuits whereby an EMF is induced in one circuit by a change of current in the other.

- **Coupling coefficient**: a number indicating the fraction of flux lines of one circuit cutting another circuit.

- **Transformer**: a device that transfers a changing current and voltage from one circuit to another through inductive coupling.
SYMBOLS AND UNITS

● Inductance symbol- L
● Inductance unit- **Henry** (h)
● Rate of current change- $\frac{di}{dt}$
● Mutual inductance- $L_M$ (or M)
● Coefficient of coupling- k
● Electromotive force- EMF ($\mathcal{E}$, measured in volts)
● Permeability- $\mu$
MAGNETIC FIELD

- A magnetic field (represented by concentric magnetic flux lines) is present around every wire that carries an electric current.
- The direction of the magnetic flux lines can be found simply by placing the thumb of the right hand in the direction of conventional current flow and noting the direction of the fingers.
MAGNETIC FIELD

Defining the flux density $B$.

Flux distribution for two adjacent, like poles.

Determining the direction of flux for an electromagnet: (a) method; (b) notation.
MAGNETIC FIELD

- In the SI system of units, magnetic flux is measured in webers \((Wb)\) as derived from the surname of Wilhelm Eduard Weber.
- The applied symbol is the capital Greek letter \(\phi\), \(\Phi\).
- The number of flux lines per unit area, called the flux density, is denoted by the capital letter \(B\) and is measured in teslas \((T)\) to honor the efforts of Nikola Tesla.

\[
1 \text{ tesla} = 1 \text{ T} = 1 \text{ Wb/m}^2
\]
MAGNETIC FIELD

- The flux density of an electromagnet is directly related to the number of turns of, and current through, the coil.
- The product of the two, called the magnetomotive force, is measured in ampere-turns (At) as defined by:

\[ F = NI \]  
(ampere-turns, At)
MAGNETIC FIELD

Milligaussmeter
ELECTRICITY AND MAGNETISM

- Inductance comes from the magnetic field around any conductor that carries current.
  - This means that electricity and magnetism are related.
- There are two laws linking electricity and magnetism.
  - Oersted's Law (discovered in 1820)
  - Faraday's Law of Induction (discovered in 1831)
Oersted's Law

- Hans Christian Oersted (Danish physicist) noticed that when a compass was located near a wire with current flow in it, the compass needle would align perpendicular to the wire.

- He concluded that any current flowing through a conductor creates a magnetic field around that conductor.
Details of Oersted’s Law

- The magnetic field lines
  - encircle the current-carrying wire and
  - lie in a plane perpendicular to the wire.
- If the direction of the current is reversed, the direction of the magnetic field reverses.
- The strength of the field
  - is directly proportional to the magnitude of the current
  - at any point is inversely proportional to the distance of the point from the wire.
Michael Faraday found that transient currents were produced in a coil of wires when a bar magnet was quickly moved in and out of the coil. The faster he moved the magnet the more current was produced. Similarly, when a conductor cuts through a magnetic field, a voltage is induced into that conductor. If the conductor creates a complete circuit, current will flow in that circuit.
FARADAY'S LAW OF INDUCTION

- Faraday’s law states that electricity comes from magnetism.
- The induced electromotive force in any closed circuit is equal to the negative of the time rate of change of the magnetic flux through the circuit:

  \[ \mathcal{E} = - \frac{d\phi_B}{dt} \]

- The negative sign is because the changing magnetic field induces a voltage back into itself in a way that opposes the original change in current.
- If there is another conductor nearby, the changing magnetic field will also induce a voltage into it.
Details of Faraday’s Law

- A steady current produces a steady magnetic field.
- Only a time varying magnetic field creates induction.
- “The observable phenomenon here depends only on the relative motion of the conductor and the magnet.” (Einstein)
- This relative motion can be because the conductor is moving, or it can be because the magnetic field is expanding or collapsing.
- This effect is summarized by Lenz’s law.
Lenz’s Law

- A changing electric current through a circuit that contains inductance induces a proportional voltage, which opposes the change in current.
  - This is called *self-inductance*.
  - The induced voltage is called CEMF, or counter electromotive force.
- The varying field in this circuit may also induce an electromotive force in neighboring circuits.
  - This is called mutual inductance.
The Meaning of Lenz’s Law

- Lenz’s Law describes how the induced electricity or magnetism acts compared to the originating electricity or magnetism.
- One important result of Lenz’s Law applies to a generator.
  - When a generator induces an electric current, the direction of the current is such that it opposes the rotation of the generator.
  - Therefore, the more electrical energy a generator delivers, the more mechanical energy is required to turn it.
INDUCTANCE

- Inductance is a property that allows conversion of one form of energy into another.
  - Electrical energy into magnetic energy
  - Magnetic energy into electrical energy
- Conversion only happens when the initial value is changing.
- This means inductance acts differently for AC vs DC.
  - An inductor offers a resistance to AC.
  - An inductor offers no resistance to DC.
INDUCTANCE

- Inductance is often described by this formula:

\[ v(t) = L \frac{di}{dt} \]

- One henry is the amount of inductance required to generate one volt of induced voltage when the current is changing at the rate of one ampere per second.
TYPE OF INDUCTANCE

- *Self-inductance*, or simply *inductance*, is the property of a circuit whereby a change in current causes a change in voltage in the same circuit.

- *Mutual inductance* is when one circuit induces current flow in a second nearby circuit.
The Derivative

- \( \frac{di}{dt} \) is read as the rate of change of current.
- \( v(t) \) is the voltage at a particular instant of time.
  - Also called EMF or electromotive force.
- Calculus has a special term used to describe a rate of change called the *derivative*.
  - \( \frac{di}{dt} \) This is where the \( d \) comes from in the formula.
- is the time derivative of current.
Opposing a Change in Current

- When voltage is increased in a circuit with inductance, some of the electrical energy goes into increasing the magnetic field, which means current does not increase immediately.
- When voltage is decreased in a circuit with inductance, the magnetic field of the inductor starts to collapse, returning electrical energy to the circuit and maintaining current.
- These effects are temporary (time-based).
Formula for the Inductance of Coils

\[ L = \frac{\mu_0 K N^2 A}{l} \]

- **Numbers of Turns (N)** - inductance varies directly with the square of the number of turns.
- **Permeability of Core (\(\mu_0\))** - inductance varies directly with the permeability of the core.
- **Cross-sectional Area of Core (A)** - inductance varies directly with the cross-sectional area of the core.
- **Length of Core (l)** - inductance varies inversely with the length of the core.
The Formula for a Henry

- The Henry is the unit of inductance.

\[ L(\text{in Henries}) = \frac{d\phi}{di} = \frac{\text{cemf}}{di/\text{dt}} \]

- One Henry of inductance is present when a one ampere change in current per second causes a CEMF of one volt.

- The henry is a relatively large unit; most inductors are measured in millihenries (mh) or microhenries (\( \mu \)h).
Types of Inductors

Air Core

Variable

Magnetic or Iron Core
Roller Inductor
Loopstick Inductor

Diagram showing the components of an adjustable 'Loopstick' inductor:
- Terminal
- Tubular Form
- Mounting Ferrule
- Coil
- Movable Ferrite Slug
- Threaded Brass Adjustment Rod

Adjustable "Loopstick" Inductor
INDUCTORS IN CIRCUITS

A. Inductors in series

1. $L_T = L_1 + L_2 + L_3 + \ldots$
   
   (NOTE: Series inductance is additive, similar to resistors in series.)

2. Series formula assumes no magnetic coupling between inductors.
Example 1.

\[ L_{total} = L_1 + L_2 + L_3 \]

\[ L_{total} = 8H + 10H + 22H \]

\[ L_{total} = 40 H \]
B. Inductors in parallel

1. Reciprocal formula:
   \[ L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}} \]

2. Unequal branch formula:
   \[ L_T = \frac{L_1 \times L_2}{L_1 + L_2} \] (useful for only two inductors)

3. Formulas assume no magnetic coupling between inductors.

4. Total inductance is less than smallest parallel branch.
Example 2:

\[ L_{(total)} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots + \frac{1}{L_n}} \]

\[ L_{(total)} = \frac{1}{\frac{1}{10} + \frac{1}{15} + \frac{1}{30}} \]

\[ = \frac{1}{\frac{3}{30} + \frac{2}{30} + \frac{1}{30}} \]

\[ L_{(total)} = \frac{1}{6/30} = 5 \, H \]
General Equations for $L_{eq}$

**Series Combination**
- If $S$ inductors are in series, then
  \[ L_{eq} = \sum_{s=1}^{S} L_s \]

**Parallel Combination**
- If $P$ inductors are in parallel, then:
  \[ L_{eq} = \left[ \sum_{p=1}^{P} \frac{1}{L_p} \right]^{-1} \]
# Parallel and Series - Formulas

<table>
<thead>
<tr>
<th></th>
<th>Capacitor</th>
<th>Resistor</th>
<th>Inductor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Series</strong></td>
<td>$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$</td>
<td>$R = R_1 + R_2$</td>
<td>$L = L_1 + L_2$</td>
</tr>
<tr>
<td><strong>Parallel</strong></td>
<td>$C = C_1 + C_2$</td>
<td>$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$</td>
<td>$\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2}$</td>
</tr>
<tr>
<td><strong>Fundamental</strong></td>
<td>$\Delta V = \frac{Q}{C}$</td>
<td>$\Delta V = IR$</td>
<td>$\mathcal{E}_L = -L \frac{dI}{dt}$</td>
</tr>
</tbody>
</table>
ENERGY STORAGE

- The flow of current through an inductor creates a magnetic field (right hand rule).

- If the current flowing through the inductor drops, the magnetic field will also decrease and energy is released through the generation of a current.
ENERGY STORAGE

- Stores energy in an magnetic field created by the electric current flowing through it.
- Inductor opposes change in current flowing through it.
- Current through an inductor is continuous; voltage can be discontinuous.
ENERGY STORAGE

- Real inductors do dissipate energy due resistive losses in the length of wire and capacitive coupling between turns of the wire.
Thank You!