Physics 25 Chapter 22 Faraday's Law Lenz's Law Dr. Joseph F. Alward



Flux Change

| Magnetic flux will change if the external field B changes, or the area of | Example: |
|---|---|
| the loop changes, or the loop's orientation (θ) changes. | The loop area is 4.0 m^2 , and doesn't change. The loop's orientation |
| Consider the example at the right. | field strength changes from 3.0 T to 4.5 T. |
| | What is the flux change? |
| | $\Phi = 4.5 (4.0) \cos 60^{\circ}$ = 9.00 T-m ² |
| | $ \Phi_{\rm o} = 3.0 \ (4.0) \ \cos \ 30^{\rm o} \\ = 10.39 \ {\rm T}{\rm -m}^2 $ |
| | $\Delta \Phi = \Phi - \Phi_0$ = 9.00 - 10.39 = -1.39 T-m ² |

Faraday's Law



Example:

Over a three-millisecond time period, the flux through a coil of 20 turns changes by $-4.0 \times 10^{-4} \text{ T-m}^2$.

What average EMF was induced in the coil?

$$\begin{split} \epsilon &= N \; |\Delta \Phi| \; /t \\ &= 20 \; (4.0 \; x \; 10^{-4}) / 0.003 \\ &= 2.67 \; V \end{split}$$





Self-Flux

Faraday's Law tells us that a changing external magnetic flux through a coil, such as might be caused by a magnet moving near the coil, induces a current in the coil.

That current creates a second field, called the "self-field," which makes the coil an equivalent bar magnet, with a north face and a south face. Do not confuse the self-field with the external field (not shown) that is causing the induced field.



Clockwise vs Counter-Clockwise Currents



Lenz's Law

We saw above that a moving magnet's field can create a second field—a self-field—in a nearby coil.

Here is Lenz's Law:

The change in external flux through a ring or coil is opposed by the coil's self-flux.

Note: the change is only opposed, not completely negated.

More generally,

The effect opposes the cause.

The effect is only to partially cancel the effect, not eliminate it entirely.

Example A:

As viewed by an observer moving with the falling magnet in the figure at the right, what is the direction of the induced current in the ring?

Cause: Magnet pulled Downward by Effect: Magnet Pushed Upward by Ring

The current must be counter-clockwise in the ring in order that the top of the ring's equivalent bar magnet be north to slow the fall of the north end of the falling magnet.



Example B:

The square ring in the figure below is being pushed into a magnetic field. The flux through the ring is changing, so a current is induced in it. What is the direction of that current ?



Cause: Increased flux external flux Effect: Opposing self-flux

As the ring is pushed into the B-field, the inward external flux into the plane increases. To counteract the increasing inward flux, an <u>outward</u> induced (self) flux (not shown) out of the plane, caused by a counter-clockwise current ring current is needed.

Alternating Current (AC) Power Supplies



Self-Flux Caused by AC Current





Example:

A coil of six turns is connected to an AC power supply whose voltage is 120 volts.

What is the AC voltage V induced in each turn?

Each turn experiences the same change in flux over the same time period, so the induced voltage is the same in every turn. By Lenz's Law, the effects (the induced voltages) oppose the cause (the AC power supply voltage): when one is positive (clockwise), the other is negative (counter-clockwise).

Let V symbolize the voltage induced in each of the six turns:

By Kirchoff's Law, the sum of the voltages is zero:

120 - 6V = 0V = 20 volts

The induced voltage per turn is 20 volts.

In general, if there are N turns, and the AC power supply voltage is \mathcal{E} , then V = \mathcal{E}/N .

Transformers Part One: The Primary



Turns of wire from an AC power supply wrap around the left side (the "primary") of an "iron donut."

The changing EMF from the AC power supply causes a changing current in each of the N_1 turns of the primary coil. In each turn, the changing current causes a changing self-flux and a self-induced voltage, V.

By the loop rule, the sum of the voltages around the primary circuit equals zero:

 $\epsilon_1 - N_1 V = 0$ Solve for V: $V = \epsilon_1/N_1$

Transformers Part Two: The Secondary

In a well-designed transformer, whatever flux flows through each of the primary turns, also flows through each of the turns on the other side--the "secondary" side. Thus, the voltage V per turn is the same for all of the turns in the primary *and* secondary.

Using the Loop Rule for the secondary circuit:

$$\begin{split} \boldsymbol{\epsilon}_2 &= N_2 V \\ &= N_2 \left(\boldsymbol{\epsilon}_1 / N_1 \right) \\ &= \left(N_2 / N_1 \right) \, \boldsymbol{\epsilon}_1 \end{split}$$

Re-written, we have "The Transformer Equation."

 $\epsilon_2 = (N_2/N_1) \epsilon_1$

Transformer Applications

Here, again, is the transformer equation:

 $\epsilon_2 = (N_2/N_1) \epsilon_1$

If N_2 is greater than N_1 , then \mathcal{E}_2 is higher than \mathcal{E}_1 . Such a transformer is called a "step up transformer."

If N_2 is less than N_1 , then \mathcal{E}_2 is lower than \mathcal{E}_1 . Such a transformer is called a "step down" transformer."

Note: While the output voltage from a step-up transformer is higher than the input voltage, the conservation of energy law tells us that *the output <u>power</u> can never be greater than the input power*. At most, the output power would equal the input power.

Also note: Some "stun" guns ("tasers") step up the voltage from a 3.0-volt battery by a factor of 1000, to 3,000 volts, which is sufficient to paralyze the large muscles of a mis-behaving human.



TASER M26C

If N_2 is less than N_1 , the secondary EMF is lower than the primary EMF, and the transformer is called a "step down transformer."

Many mobile electronic devices have batteries that are charged at a voltage between 3.0 and 9.0 volts using a step-down transformer connected to a 120-volt AC wall outlet.



Transmission Line Power Loss



Electricity is often generated dozens of miles from where it is used. Although the resistance of a short length of power line is relatively low, over a long distance the resistance is substantial.

A power line of resistance R carrying current I loses energy at the rate $P = I^2 R$. By minimizing the output current, the $I^2 R$ power losses can be reduced to acceptable levels.

The example below addresses the question of power line losses.

Example:

The resistance per mile of typical power lines is very small--about 0.40 Ω per mile. (Compare this to the 200-ohm resistance of a 60-watt incandescent light bulb filament.)

Consider a power plant outputting 10 megawatts (MW) of electrical power, destined for a city 20 miles away.

 $P = I\varepsilon$ $= 1.0 \text{ x } 10^7 \text{ W}$

This power can be created in an uncountable number of ways; the only requirement is that

the product of the output current I and EMF ϵ be 1.0 x $10^7\,W.$

Suppose the output current and voltage are 1.0×10^3 A, and 1.0×10^4 V. What would be the percentage power loss due to I²R heating?

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R = (0.40 \text{ Ω/mi}) (20 \text{ mi})
= 8.0 Ω
P = I^2 R
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= 1000^{2} (8.0)
= 8.0 x 10<sup>6</sup>
= 8.0 MW
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Percentage Lost = (8.0/10.0) 100% = 80% Another Power Loss Example

For the power plant in the example above, what would have to be the output voltage and current in order that the loss be only 5% ? $P = 0.05 (10.0) = 0.50 \text{ MW} = 5.0 \text{ x } 10^5 \text{ W}$ $I^2 (8.0) = 5.0 \text{ x } 10^5 \text{ I} = 250 \text{ A}$ $\mathcal{E}(250) = 1.0 \text{ x } 10^7 \text{ E} = 40,000 \text{ V}$ A series of step-down transformers at sub-stations close to the city provides the 110-V and 220-V voltages needed by electrical

devices in the home and factory.