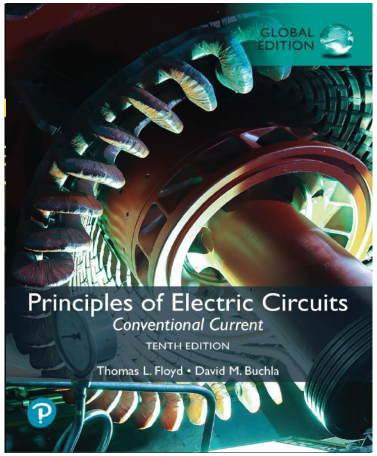
Principles of Electric Circuits: Conventional Current

Tenth Edition, Global Edition

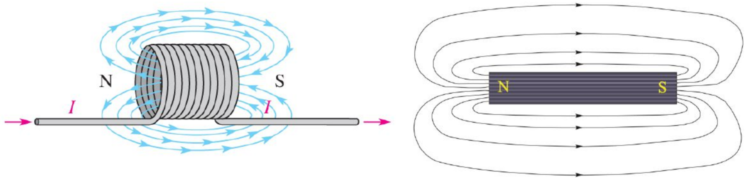


Chapter 14

Inductors

Summary: Inductance (1 of 3)

Inductance is the property of a conductor to oppose a *change* in current. The effect of inductance is greatly magnified by winding a coil on a magnetic material. When there is current in the coil, a magnetic field is generated, similar to that of a bar magnet.



Summary: Self Inductance (2 of 3)

Self-inductance is usually just called inductance, symbolized by *L*. Self-inductance is a measure of a coil's ability to establish an induced voltage as a result of a *change* in its current.

The unit of inductance is the **henry (H)**. One henry is the inductance of a coil when a current, changing at a rate of one ampere per second, induces one volt across the coil.

This induced voltage is given by the formula $v_{ind} = L\frac{di}{dt}$

where

v_{ind} = induced voltage in volts

L = inductance in henries

$\frac{di}{dt}$ = rate of change of current in amperes per second

Summary: Self Inductance (3 of 3)

Example:

What is the inductance if 10.3 mV is induced across a coil if the current is changing at a rate of 680 mA/s?

$$v_{ind} = L\frac{di}{dt}$$

$$L = \frac{v_{ind}}{di/dt} = \frac{10.3\text{ mV}}{680\text{ mA/s}} = 15.1\text{mH}$$

Question:

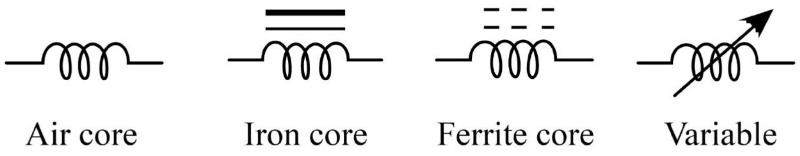
What will happen if the rate of change of current increases?

The induced voltage will increase, opposing the change in current.

Physical characteristics of inductors

An inductor is basically a coil of wire that surrounds a magnetic or nonmagnetic material called the **core**. Examples of magnetic materials are iron, nickel, steel, cobalt, or alloys. Inductor symbols are based on the core material.

Common symbols for inductors (coils) are:

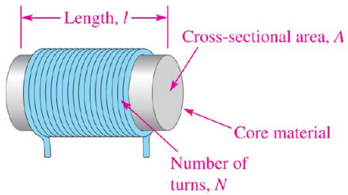


Summary: Factors affecting inductance (1 of 3)

The inductance of a coil is dependent upon four factors: $L = \frac{N^2 \mu A}{l}$

where

- L = inductance in henries
- N = number of turns of wire
- μ = permeability in H/m (same as Wb/At·m)
- A = cross-sectional area
- l = coil length on meters



Permeability varies greatly with different materials; high permeability cores can increase the inductance by thousands of times over air.

Summary: Factors affecting inductance (2 of 3)

Example

What is the inductance of a 2.0 cm long, 150 turn coil wrapped on an low carbon steel core that is 0.50 cm diameter? The permeability of low carbon steel is 2.5 x10^{-4} H/m (Wb/At-m).

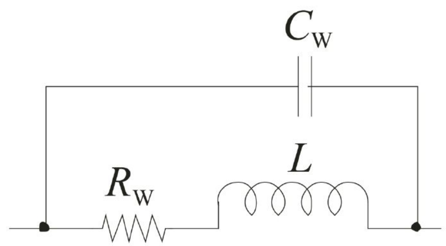
$$L = \frac{N^2 \mu A}{l}$$

$$= \frac{(150\ \text{t})^2 \left(2.5\times10^{-4}\ \text{Wb/At-m}\right)\left(1.96\times10^{-5}\ \text{m}^2\right)}{0.020\ \text{m}}$$

$$= 5.52\ \text{mH}$$

Summary: Factors affecting inductance (3 of 3)

The inductance given by the equation in the previous slide is for the ideal case. In practice, inductors have winding resistance (R_W) and winding capacitance (C_W). An equivalent circuit for a practical inductor including these effects is:



Summary: Faraday's law (review)

Recall that Faraday's law can be written as $v_{\text{ind}} = N\left(\frac{d\phi}{dt}\right)$.

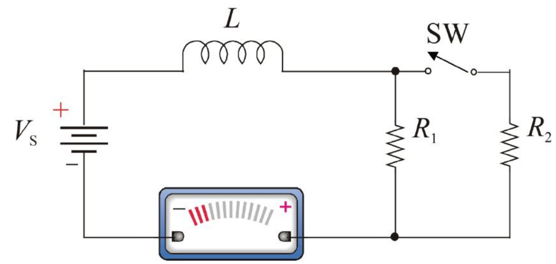
Faraday's law states that the induced voltage across a coil is equal to the number of turns (loops) times the rate of flux *change*. The key term here is *change*.

Lenz's law added the concept that the polarity of the induced voltage is such that it *opposes* the change. Thus, if a current in a coil tries to change the flux, a voltage is generated to oppose that change.

Summary: Lenz's law (1 of 3)

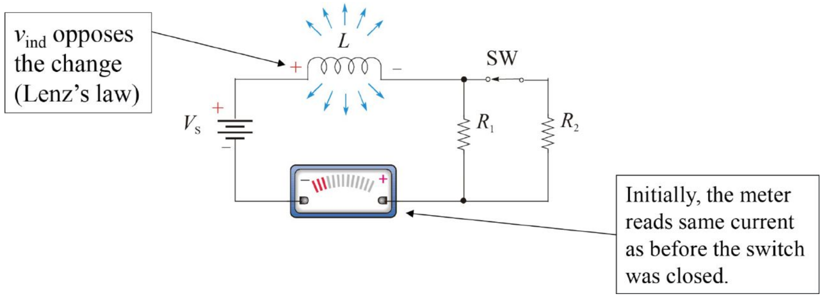
The effect of a change in current is illustrated below:

Initially, the SW is open and there is a small current in the circuit through L and R_1 as indicated on the meter.



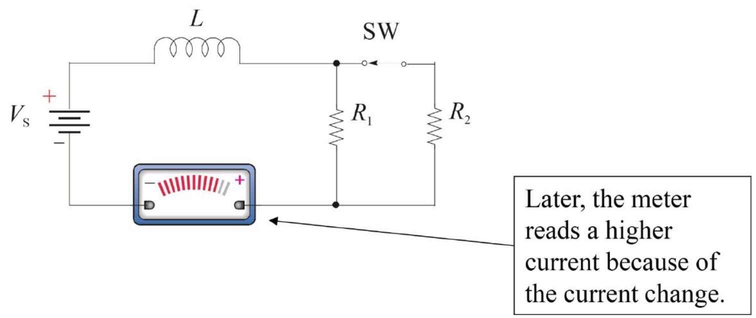
Summary: Lenz's law (2 of 3)

SW closes and immediately a voltage appears across L that tends to oppose any *change* in current.



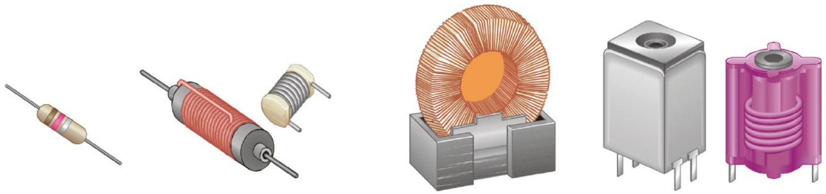
Summary: Lenz's law (3 of 3)

After a time, the current stabilizes at a higher level (due to I_2) as the voltage decays across the coil.



Summary: Practical inductors

Inductors come in a variety of sizes. A few common ones are shown here.



Encapsulated   Wirewound (high current)   Torroid coil   Variable

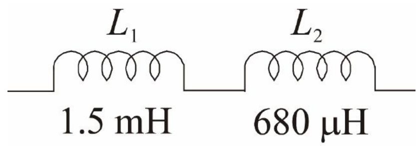
Summary: Series inductors

When inductors are connected in series, the total inductance is the sum of the individual inductors. The general equation for inductors in series is

$$L_T = L_1 + L_2 + L_3 + \ldots L_n$$

Example

If a 1.5 mH inductor is connected in series with an 680 mH inductor, the total inductance is 2.18 mH



Summary: Parallel inductors (1 of 2)

When inductors are connected in parallel, the total inductance is smaller than the smallest one. The general equation for inductors in parallel is

$$L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots + \frac{1}{L_n}}$$

The total inductance of two inductors is

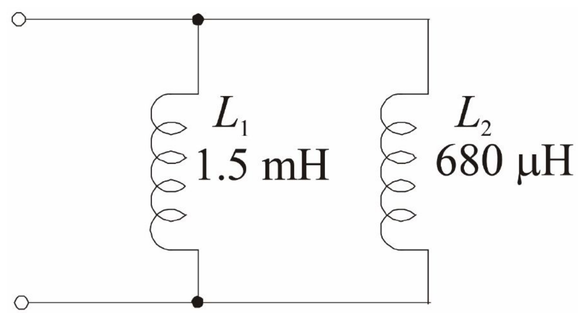
$$L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2}}$$

…or you can use the product-over-sum rule with two inductors.

Summary: Parallel inductors (2 of 2)

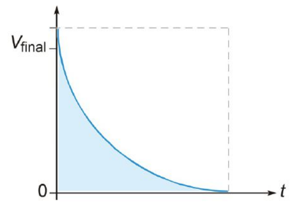
Example

If a 1.5 mH inductor is connected in parallel with an 680 μH inductor, the total inductance is 468 μH

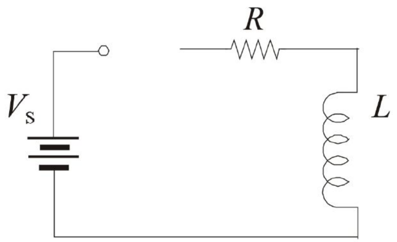


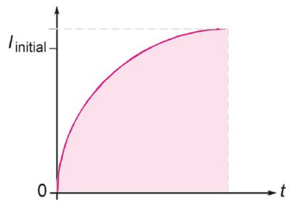
Summary: Inductors in dc circuits
(1 of 2)

When an inductor is connected in series with a resistor and dc source, the current change is exponential.



Inductor voltage after switch closure

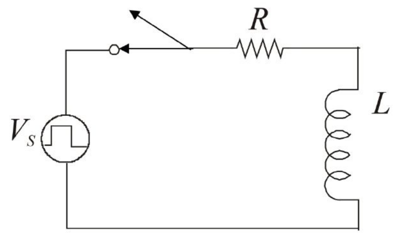


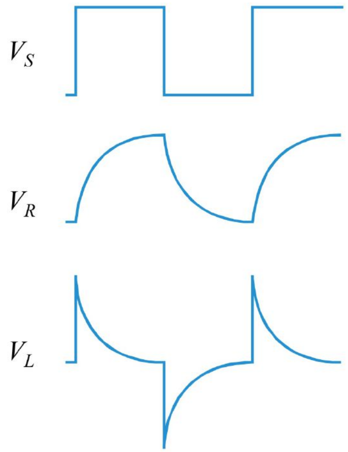


Current after switch closure

Summary: Inductors in dc circuits
(2 of 2)

The same shape curves are seen if a square wave is used for the source.





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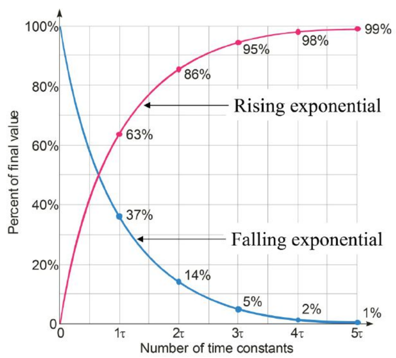
Summary: Universal exponential curves (1 of 5)

Specific values for current and voltage can be read from a universal curve. For an *RL* circuit, the time constant is

$$\tau = \frac{L}{R}$$

For the rising exponential, 5t is typically considered to be 100%. For the falling exponential, 5t is typically considered to be 0%.



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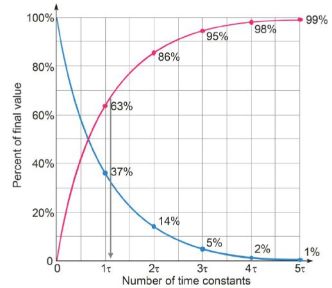
Summary: Universal exponential curves (2 of 5)

The curves can give specific information about an *RL* circuit.

Example

In a series *RL* circuit, when is $V_R > 2V_L$?

Read the rising exponential at the 67% level. After 1.1 τ



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Summary: Universal exponential curves (3 of 5)

Example

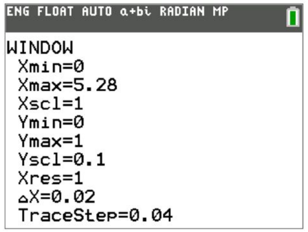
Plot the normalized universal exponential curves on the T I-84 Plus CE calculator.

The equations for a rising and falling exponential curves are

$$y = 1 - e^{-x} \quad (\text{rising})$$

$$y = -e^{-x} \quad (\text{falling})$$

Graph parameters are shown



Summary: Universal exponential curves (4 of 5)

Example

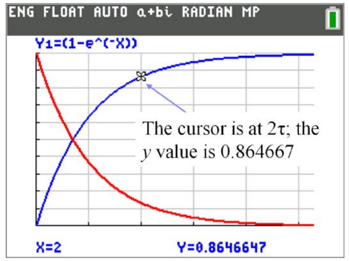
Plot the normalized universal exponential curves on the T I-84 Plus CE calculator.

The equations for a rising and falling exponential curves are

$$y = 1 - e^{-x} \quad (\text{rising})$$

$$y = -e^{-x} \quad (\text{falling})$$

The graph is



Summary: Universal exponential curves (5 of 5)

The universal curves can be applied to general formulas for the current (or voltage) curves for *RL* circuits. The general current formula is

$i = I_F + (I_i - I_F)e^{-Rt/L}$

I_F = final value of current

I_i = initial value of current

i = instantaneous value of current

The final current is greater than the initial current when the inductive field is building, or less than the initial current when the field is collapsing.

Summary: Inductive reactance

Inductive reactance is the opposition to ac by an inductor. The equation for inductive reactance is

$$X_L = 2\pi fL$$

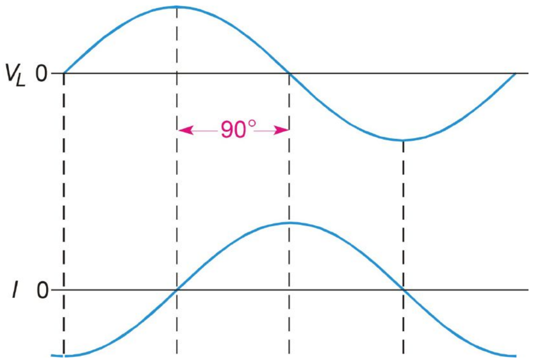
Examples

a. The reactance of a 33 mH inductor when a frequency of 550 kHz is applied is 114 Ω

b. What size inductor will have a reactance of 10 kW at 40 MHz? 39.8 μH

Summary: Inductive phase shift

When a sine wave is applied to an inductor, there is a phase shift between voltage and current such that voltage always leads the current by 90°.



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Summary: Power in an inductor

True Power: Ideally, inductors do not dissipate power. However, a small amount of power is dissipated in the winding resistance, given by the equation:

$$P_{true} = (I_{rms})^2 R_W$$

Reactive Power: Reactive power is a measure of the rate at which the inductor stores and returns energy. One form of the reactive power equation is:

$$P_r = V_{rms} I_{rms}$$

The unit for reactive power is the VAR.

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Summary: *Q* of an inductor

The **quality factor (*Q*)** for an inductor is given by the ratio of reactive power to true power. Note that *Q* is defined only at a specific frequency because X_L is frequency dependent.

$$Q = \frac{I^2 X_L}{I^2 R_W}$$

For a series circuit, *I* cancels, leaving

$$Q = \frac{X_L}{R_W}$$

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Key Terms (1 of 2)

Inductor An electrical device, formed by a wire wound around a core, having the property of inductance; also known as a coil.

Winding The loops or turns of wire in an inductor.

Induced voltage Voltage produced as a result of a changing magnetic field.

Inductance The property of an inductor whereby a change in current causes the inductor to produce a voltage that opposes the change in current.

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Key Terms (2 of 2)

***Henry* (H)** The unit of inductance.

RL time constant A fixed time interval, set by the *L* and *R* values, that determines the time response of a circuit. It equals the ratio of *L*/*R*.

Inductive reactance The opposition of an inductor to sinusoidal current. The unit is the ohm.

Quality factor The ratio of reactive power to true power for an inductor.

Quiz (1 of 11)

1. Assuming all other factors are the same, the inductance of an inductor will be larger if

   a. more turns are added
   b. the area is made larger
   c. the length is shorter
   d. all of the above

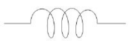
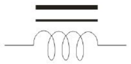
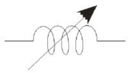
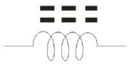
Quiz (2 of 11)

2. The henry is defined as the inductance of a coil when

   a. a constant current of one amp develops one volt.
   b. one volt is induced due to a change in current of one amp per second.
   c. one amp is induced due to a change in voltage of one volt.
   d. the opposition to current is one ohm.

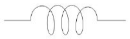
Quiz (3 of 11)

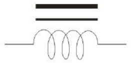
3. The symbol for a ferrite core inductor is

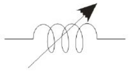
   a. 
   b. 
   c. 
   d. 

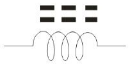
Quiz (4 of 11)

4. The symbol for a variable inductor is

a. 

b. 

c. 

d. 

Quiz (5 of 11)

5. The total inductance of a 270 μH inductor connected in series with a 1.2 mH inductor is

a. 220 μH
b. 271 μH
c. 599 μH
d. 1.47 μH

Quiz (6 of 11)

6. The total inductance of a 270 μH inductor connected in parallel with a 1.2 mH inductor is

a. 220 μH
b. 271 μH
c. 599 μH
d. 1.47 μH

Quiz (7 of 11)

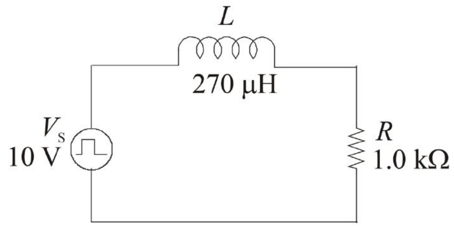
7. When an inductor is connected through a series resistor and switch to a dc voltage source, the voltage across the resistor after the switch closes has the shape of

a. a straight line
b. a rising exponential
c. a falling exponential
d. none of the above

Quiz (8 of 11)

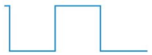
8. For circuit shown, the time constant is

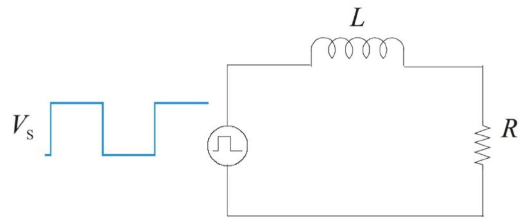
   a. 270 ns
   b. 270 μs
   c. 270 ms
   d. 3.70 s



Quiz (9 of 11)

9. For circuit shown, assume the period of the square wave is 10 times longer than the time constant. The shape of the voltage across L is

   a. 
   b. 
   c. 
   d. 



Quiz (10 of 11)

10. If a sine wave from a function generator is applied to an inductor, the current will

   a. lag voltage by 90°
   b. lag voltage by 45°
   c. be in phase with the voltage
   d. none of the above

Quiz (11 of 11)

Answers:

1. d
2. b
3. d
4. c
5. d
6. a
7. b
8. a
9. c
10. a