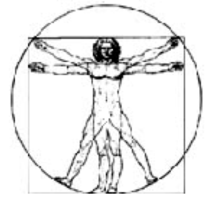
Electrical and Computer Engineering

ELEC 391
Electrical Engineering Design Studio



Practical Inductors and Capacitors

Introduction to project management. Problem definition. Design principles and practices. Implementation techniques including circuit design, software design, solid modeling, PCBs, assembling, and packaging. Testing and evaluation. Effective presentations. Pre-requisite: Two of EECE 352, EECE 356, EECE 359, EECE 360, EECE 364, EECE 373. [2-6-0]

- During this lecture, the instructor will bring up many points and details not given on these slides. Accordingly, it is expected that the student will annotate these notes during the lecture.
- The lecture only introduces the subject matter. Students must review these notes after class and complete the reading assignments and problems if they are to master the material.

Learning Objectives

Describe the construction of a capacitor and how charge is stored.

Introduce several types of capacitors

Discuss the electrical properties of a capacitor

- The relationship between charge, voltage, and capacitance
  - Charging and discharging of a capacitor
- Relationship between voltage, current, and capacitance; power; and energy
- Equivalent capacitance when a set of capacitors are in series and in parallel

Capacitors

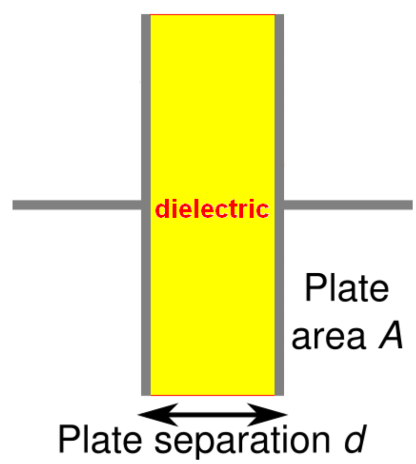
- Composed of two conductive plates separated by an insulator (or dielectric).
- Commonly illustrated as two parallel metal plates separated by a distance, d.

$$C = \varepsilon A/d$$

where $\varepsilon = \varepsilon_r \varepsilon_o$

ε_r is the relative dielectric constant

ε_o is the vacuum permittivity



Effect of Dimensions

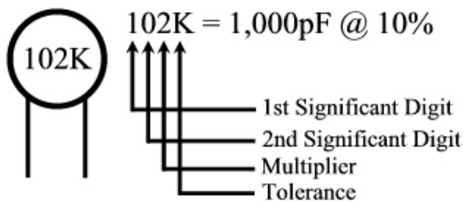
- Capacitance increases with
  - increasing surface area of the plates,
  - decreasing spacing between plates, and
  - increasing the relative dielectric constant of the insulator between the two plates.

Types of Capacitors

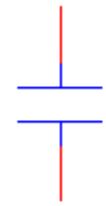
- Fixed Capacitors
  - Nonpolarized
    - May be connected into circuit with either terminal of capacitor connected to the high voltage side of the circuit.
      - Insulator: Paper, Mica, Ceramic, Polymer
  - Electrolytic
    - The negative terminal must always be at a lower voltage than the positive terminal
      - Plates or Electrodes: Aluminum, Tantalum

Nonpolarized

- Difficult to make nonpolarized capacitors that store a large amount of charge or operate at high voltages.
  - Tolerance on capacitance values is very large
    - +50%/-25% is not unusual



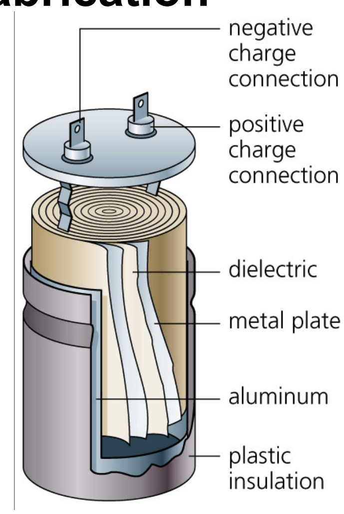
PSpice Symbol



Electrolytic

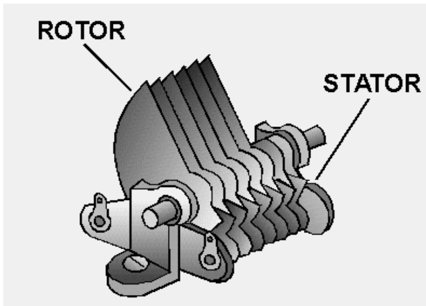
Pspice Symbols

Fabrication

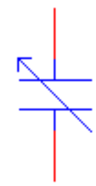


Variable Capacitors

- Cross-sectional area is changed as one set of plates are rotated with respect to the other.

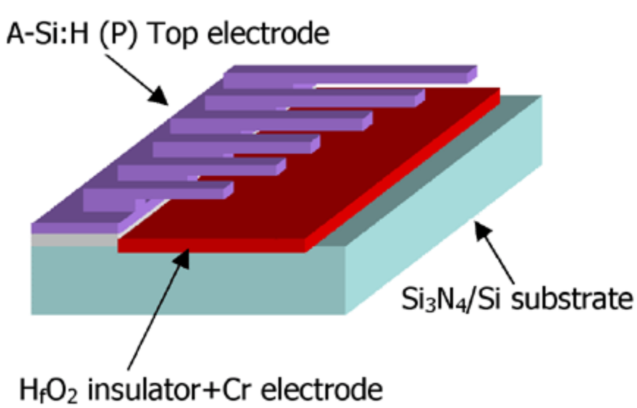


PSpice Symbol



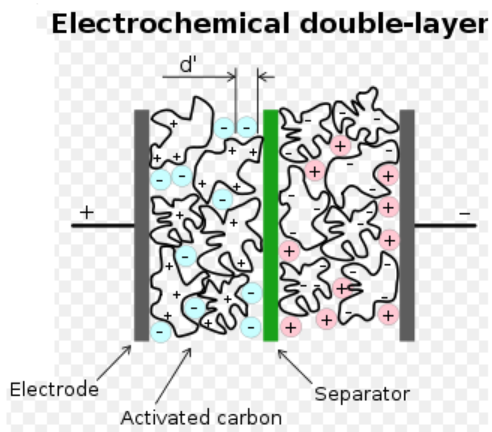
MEMS Capacitor

- MEMS (<u>M</u>icro<u>e</u>lectro<u>m</u>echanical <u>s</u>ystem)
  - Can be a variable capacitor by changing the distance between electrodes.
  - Use in sensing applications as well as in RF electronics.



Electric Double Layer Capacitor

- Also known as a supercapacitor or ultracapacitor
  - Used in high voltage/high current applications.
    - Energy storage for alternate energy systems.

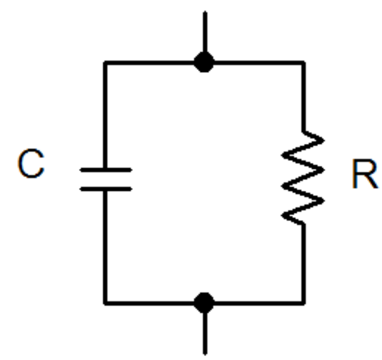


Electrical Properties of a Capacitor

- Acts like an open circuit at steady state when connected to a DC voltage or current source.
- Voltage on a capacitor must be continuous
  - There are no abrupt changes to the voltage, but there may be discontinuities in the current.
- An ideal capacitor does not dissipate energy, it takes power when storing energy and returns it when discharging.

Properties of a Real Capacitor

- A real capacitor does dissipate energy due leakage of charge through its insulator.
  - This is modeled by putting a resistor in parallel with an ideal capacitor.



Energy Storage

- Charge is stored on the plates of the capacitor.

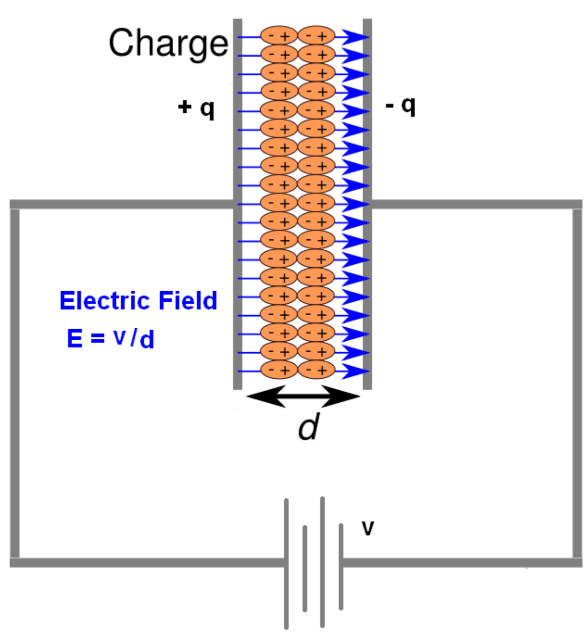
Equation:

$$Q = CV$$

Units:

Farad = Coulomb/Voltage

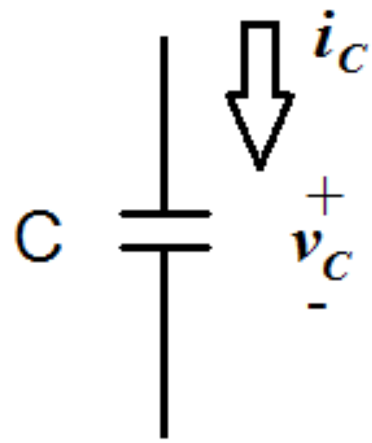
Farad is abbreviated as F



Sign Conventions

The sign convention used with a capacitor is the same as for a power dissipating device.

- When current flows into the positive side of the voltage across the capacitor, it is positive and the capacitor is dissipating power.
- When the capacitor releases energy back into the circuit, the sign of the current will be negative.



Charging a Capacitor

At first, it is easy to store charge in the capacitor.

As more charge is stored on the plates of the capacitor, it becomes increasingly difficult to place additional charge on the plates.

- Coulombic repulsion from the charge already on the plates creates an opposing force to limit the addition of more charge on the plates.
  - Voltage across a capacitor increases rapidly as charge is moved onto the plates when the initial amount of charge on the capacitor is small.
  - Voltage across the capacitor increases more slowly as it becomes difficult to add extra charge to the plates.

Adding Charge to Capacitor

- The ability to add charge to a capacitor depends on:
  - the amount of charge already on the plates of the capacitor

  and
  - the force (voltage) driving the charge towards the plates (i.e., current)

Discharging a Capacitor

At first, it is easy to remove charge in the capacitor.

- Coulombic repulsion from charge already on the plates pushes some of the charge out of the capacitor once the force (voltage) that placed the charge in the capacitor is removed (or decreased).

As more charge is removed from the plates of the capacitor, it becomes increasingly difficult to get rid of the small amount of charge remaining on the plates.

- Coulombic repulsion decreases as charge spreads out on the plates. As the amount of charge decreases, the force needed to drive the charge off of the plates decreases.
  - Voltage across a capacitor decreases rapidly as charge is removed from the plates when the initial amount of charge on the capacitor is small.
  - Voltage across the capacitor decreases more slowly as it becomes difficult to force the remaining charge out of the capacitor.

General Equations for C_{eq}

Parallel Combination

- If P capacitors are in parallel, then

$$C_{eq} = \sum_{p=1}^{P} C_P$$

Series Combination

- If S capacitors are in series, then:

$$C_{eq} = \left[\sum_{s=1}^{S} \frac{1}{C_s} \right]^{-1}$$

Summary

- Capacitors are energy storage devices.
- An ideal capacitor act like an open circuit at steady state when a DC voltage or current has been applied.
- The voltage across a capacitor must be a continuous function; the current flowing through a capacitor can be discontinuous.

$$i_C = C \frac{dv_C}{dt} \qquad v_C = \frac{1}{C} \int_{t_0}^{t_1} i_C \, dt$$

- The equations for equivalent capacitance for

capacitors in parallel

$$C_{eq} = \sum_{p=1}^{P} C_P$$

capacitors in series

$$C_{eq} = \left[\sum_{s=1}^{S} \frac{1}{C_s} \right]^{-1}$$

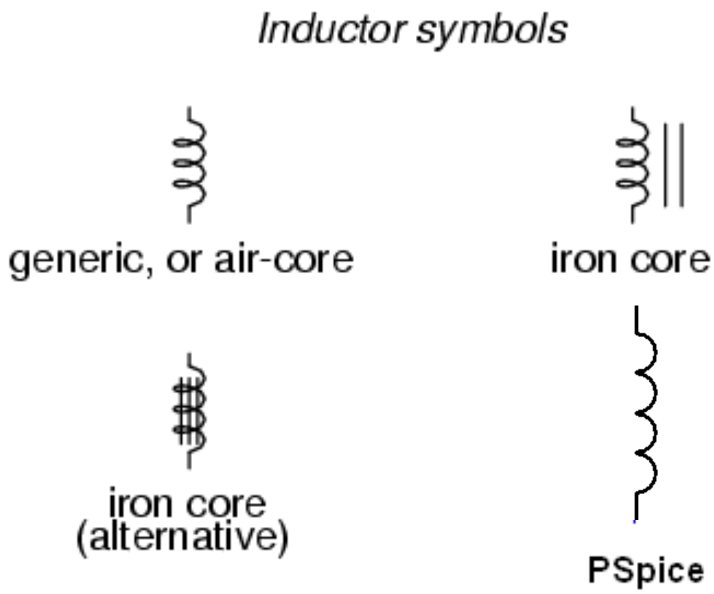
Objective of Lecture

- Describe
  - The construction of an inductor
  - How energy is stored in an inductor
  - The electrical properties of an inductor
    - Relationship between voltage, current, and inductance; power; and energy
  - Equivalent inductance when a set of inductors are in series and in parallel

Inductors

- Generally - coil of conducting wire
  - Usually wrapped around a solid core. If no core is used, then the inductor is said to have an 'air core'.

Symbols



Alternative Names for Inductors

Reactor- inductor in a power grid

Choke - designed to block a particular frequency while allowing currents at lower frequencies or d.c. currents through

- Commonly used in RF (radio frequency) circuitry

Coil - often coated with varnish and/or wrapped with insulating tape to provide additional insulation and secure them in place

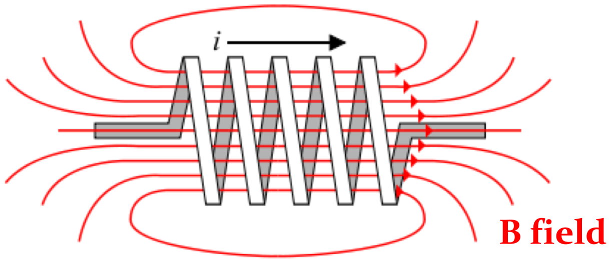
- A winding is a coil with taps (terminals).

Solenoid – a three dimensional coil.

- Also used to denote an electromagnet where the magnetic field is generated by current flowing through a toroidal inductor.

Energy Storage

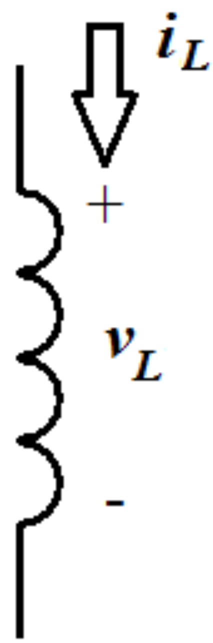
The flow of current through an inductor creates a magnetic field (right hand rule).



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

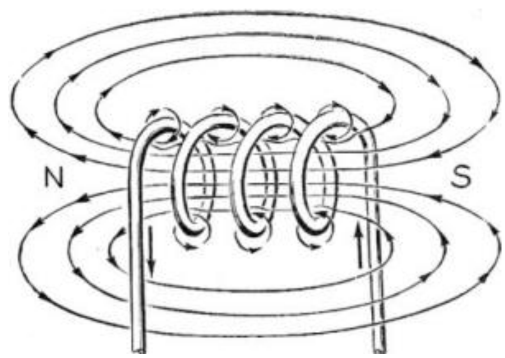
Sign Convention

- The sign convention used with an inductor is the same as for a power dissipating device.
  - When current flows into the positive side of the voltage across the inductor, it is positive and the inductor is dissipating power.
  - When the inductor releases energy back into the circuit, the sign of the current will be negative.



Inductors

- 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.



Calculations of L

For a solenoid (toroidal inductor)

$$L = \frac{N^2 \mu A}{\ell} = \frac{N^2 \mu_r \mu_o A}{\ell}$$

N is the number of turns of wire

A is the cross-sectional area of the toroid in m^2.

μ_r is the relative permeability of the core material

μ_o is the vacuum permeability ($4\pi \times 10^{-7}$ H/m)

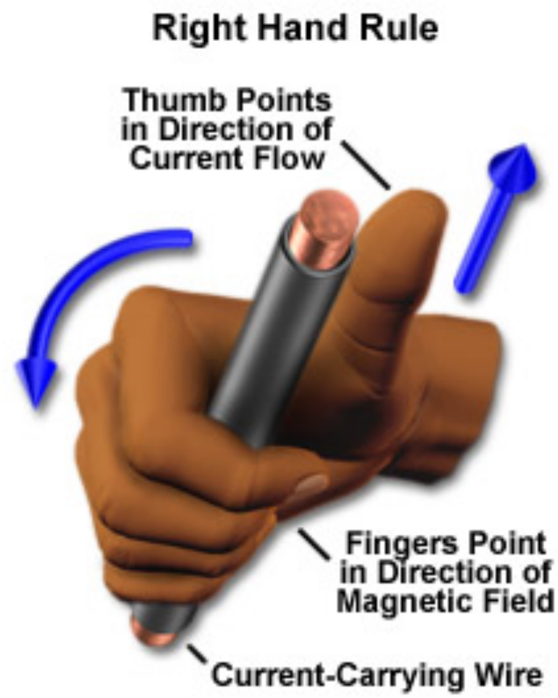
ℓ is the length of the wire used to wrap the toroid in meters

Wire

Unfortunately, even bare wire has inductance.

$$L = \ell\left[\ln\left(4\frac{\ell}{d}\right) - 1\right]\left(2x10^{-7}\right)H$$

d is the diameter of the wire in meters.

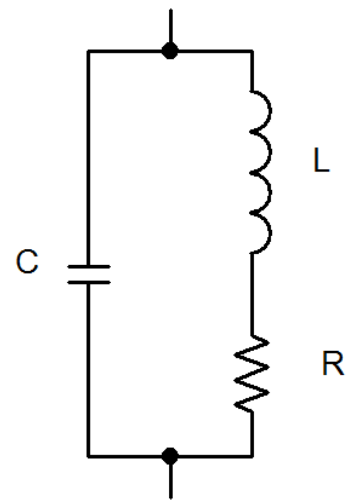


Properties of an Inductor

- Acts like an short circuit at steady state when connected to a d.c. voltage or current source.
- Current through an inductor must be continuous
  - There are no abrupt changes to the current, but there can be abrupt changes in the voltage across an inductor.
- An ideal inductor does not dissipate energy, it takes power from the circuit when storing energy and returns it when discharging.

Properties of a Real Inductor

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



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:

$$L_{eq} = \left[\sum_{p=1}^{P} \frac{1}{L_p} \right]^{-1}$$

Summary

- Inductors are energy storage devices.
- An ideal inductor act like a short circuit at steady state when a DC voltage or current has been applied.
- The current through an inductor must be a continuous function; the voltage across an inductor can be discontinuous.
- The equation for equivalent inductance for

inductors in series

$$L_{eq} = \sum_{s=1}^{S} L_s$$

inductors in parallel

$$L_{eq} = \left[\sum_{p=1}^{P} \frac{1}{L_p} \right]^{-1}$$