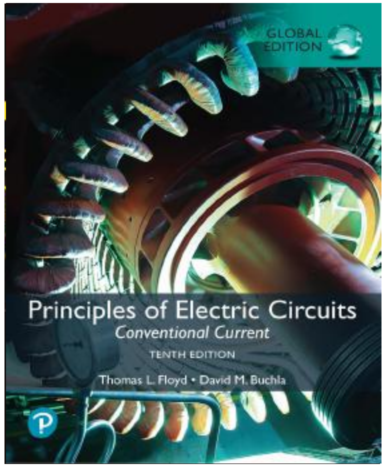
Principles of Electric Circuits: Conventional Current

Tenth Edition, Global Edition



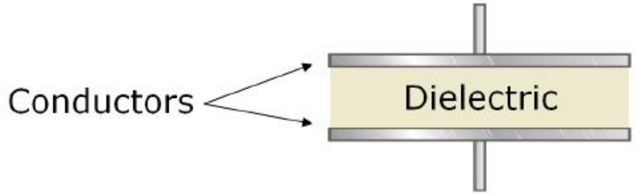
Chapter 12

Capacitors

Summary: The Capacitor (1 of 5)

Capacitors are one of the fundamental passive components. In its most basic form, it is composed of two plates separated by an insulating material or dielectric.

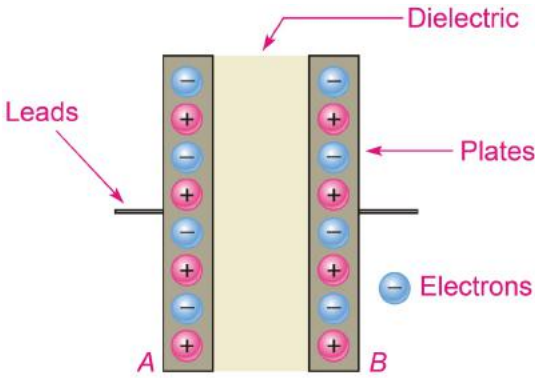
The ability to store charge is the definition of **capacitance**.



Summary: The Capacitor (2 of 5)

The charging process…

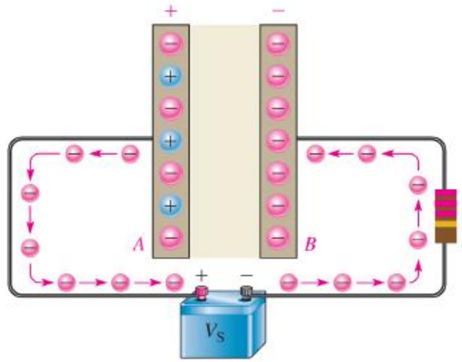
Initially uncharged



Summary: The Capacitor (3 of 5)

The charging process…

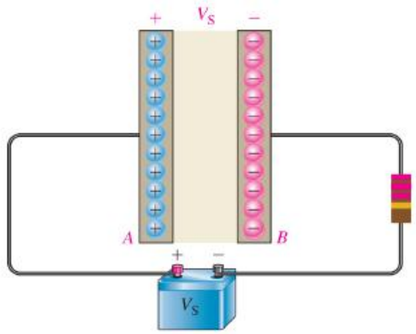
Charging



Summary: The Capacitor (4 of 5)

The charging process…

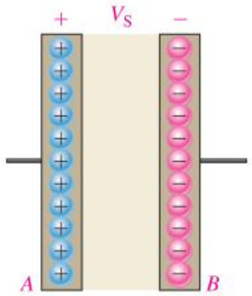
Fully charged



Summary: The Capacitor (5 of 5)

The charging process…

Source removed



A capacitor with stored charge can act as a temporary source of electrical energy.

Summary: Capacitance

Capacitors have a maximum voltage that cannot be exceeded before breakdown. Dielectric strength is expressed as the maximum voltage per mil that a material can withstand. Some common dielectric materials and their dielectric strengths are:

Material	Dielectric Strength (V/MIL)
Air	80
Oil	375
Ceramic	1,000
Paper (paraffined)	1,200
Teflon®	1,500
Mica	1,500
Glass	2,000

Capacitance (1 of 3)

Capacitance is the ratio of charge to voltage

$$C = \frac{Q}{V}$$

Rearranging, the amount of charge on a capacitor is determined by the size of the capacitor (*C*) and the voltage (*V*).

$$Q = CV$$

Example:

If a 22 μF capacitor is connected to a 10 V source, the charge is 220 μC

Capacitance (2 of 3)

An analogy:

Imagine you store rubber bands in a bottle that is nearly full.

You could store more rubber bands (like charge or *Q*) in a bigger bottle (capacitance or *C*) *or* if you push them in with more force (voltage or *V*). Thus,

$$Q = CV$$

Capacitance (3 of 3)

A capacitor stores energy in the form of an electric field that is established by the opposite charges on the two plates. The energy of a charged capacitor is given by the equation

$$W = \frac{1}{2}CV^2$$

where

W = the energy in joules

C = the capacitance in farads

V = the voltage in volts

Example

How much energy is stored in a 10,000 μF capacitor charged to 24 V? 2.88 J

Summary: Capacitance (1 of 3)

The capacitance of a capacitor depends on three physical characteristics.

$$C = 8.85 \times 10^{-12}\ \text{F/m}\left(\frac{\varepsilon_r A}{d}\right)$$

C is directly proportional to the **relative dielectric constant** and the **plate area.**

C is inversely proportional to the **distance** between the plates

Summary: Capacitance (2 of 3)

The relative dielectric constant, ε_r, is also known as relative permittivity. It is a measure of how much a given material concentrates electric flux relative to a vacuum (ε_r =1 for a vacuum).

Some relative permittivity value are shown in the table:

Material	Typical ε_r Value
Air (vacuum)	1.0
Teflon	2.0
Paper (paraffined)	2.5
Oil	4.0
Mica	5.0
Glass	7.5
Ceramic	1,200

Summary: Capacitance (3 of 3)

Find the capacitance of a 4.0 cm diameter sensor immersed in oil if the plates are separated by 0.25 mm.

$(\varepsilon_r = 4.0 \text{ for oil})$

Example

$$C = 8.85\times10^{-12}\,\text{F/m}\left(\frac{\varepsilon_r A}{d}\right)$$

The plate area is $A = \pi r^2 = \pi\left(0.02\ \text{m}^2\right) = 1.26\times10^{-3}\ \text{m}^2$

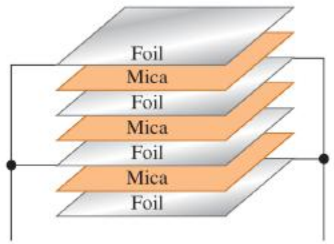
The distance between the plates is $0.25\times10^{-3}\ \text{m}$

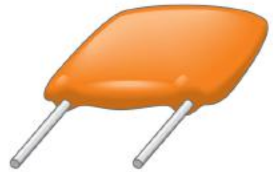
$$C = 8.85\times10^{-12}\,\text{F/m}\left(\frac{(4.0)\left(1.26\times10^{-3}\ \text{m}^2\right)}{0.25\times10^{-3}\ \text{m}}\right) = 178\ \text{pF}$$

Summary: Capacitor types (1 of 5)

Mica

Mica capacitors are small with high working voltage. The **working voltage** is the voltage limit that cannot be exceeded without damaging the capacitor.

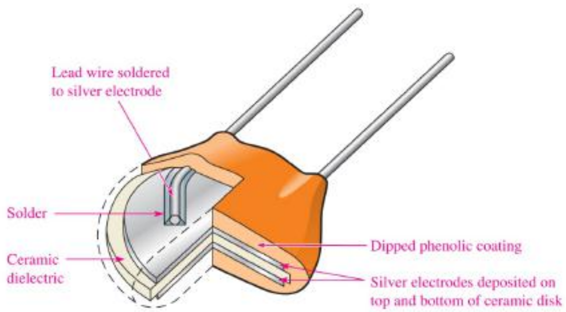




Summary: Capacitor types (2 of 5)

Ceramic disk

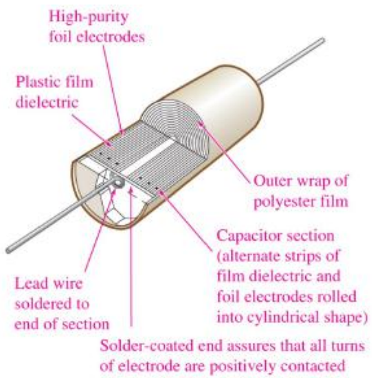
Ceramic disks are small nonpolarized capacitors They have relatively high capacitance due to high ε_r.



Summary: Capacitor types (3 of 5)

Plastic Film

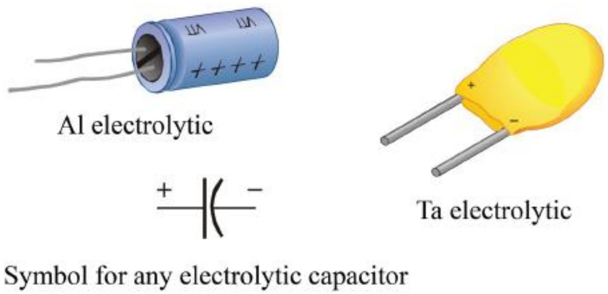
Plastic film capacitors are small and nonpolarized. They have relatively high capacitance due to larger plate area.



Summary: Capacitor types (4 of 5)

Electrolytic (two types)

Electrolytic capacitors have very high capacitance but they are not as precise as other types and tend to have more leakage current. Electrolytic types are polarized.

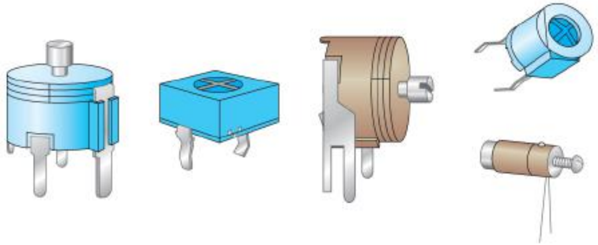


Summary: Capacitor types (5 of 5)

Variable

Variable capacitors typically have small capacitance values and are usually adjusted manually.

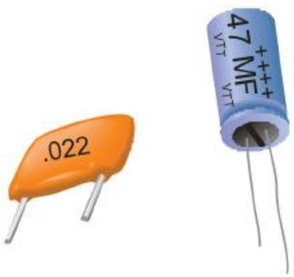
A solid-state device that is used as a variable capacitor is the varactor diode; it is adjusted with an electrical signal.



Capacitor labeling (1 of 2)

Capacitors use several labeling methods. Small capacitors values are frequently stamped on them such as .001 or .01, which have units of microfarads.

Electrolytic capacitors have larger values, so are read as mF. The unit is usually stamped as mF, but some older ones may be shown as MF or MMF).



Capacitor labeling (2 of 2)

A label such as 103 or 104 is read as 10×10^3 (10,000 pF) or 10×10^4 (100,000 pF) respectively. (Third digit is the multiplier.)

When values are marked as 330 or 6800, the units are picofarads.

Example

a. What is the value of each capacitor? Both are 2200 pF.

b. What is the value of a capacitor marked 682? 6800 pF.

Summary: Series capacitors (1 of 2)

When capacitors are connected in series, the total capacitance is smaller than the smallest one. The general equation for capacitors in series is:

$$C_T = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\ldots+\frac{1}{C_n}}$$

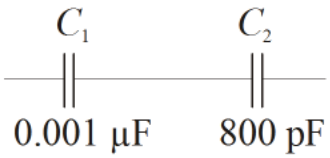
The total capacitance of two series capacitors is: $C_T = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}}$

This reduces to the product-over-sum rule: $C_T = \frac{C_1 C_2}{C_1 + C_2}$

Summary: Series capacitors (2 of 2)

Example

If a 0.001 μF capacitor is connected in series with an 800 pF capacitor, the total capacitance is 444 pF



Follow-up:

If another 0.001 mF capacitor is connected in series with the capacitors, the total capacitance is 308 pF

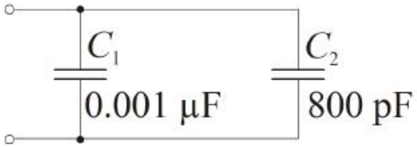
Summary: Parallel capacitors

When capacitors are connected in parallel, the total capacitance is the sum of the individual capacitors. The general equation for capacitors in parallel is

$$C_T = C_1 + C_2 + C_3 + \ldots C_n$$

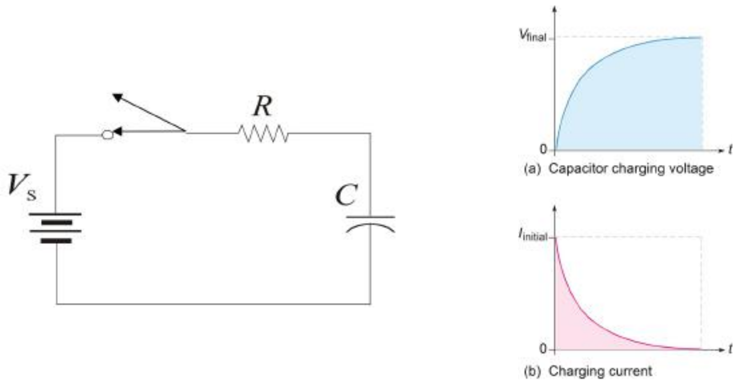
Example

If a 0.001 μF capacitor is connected in parallel with an 800 pF capacitor, the total capacitance is 1800 pF



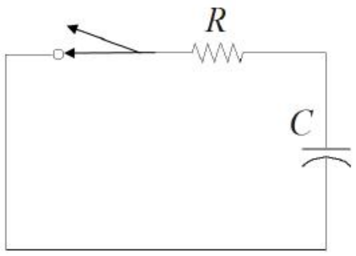
Summary: Capacitors in dc circuits (1 of 2)

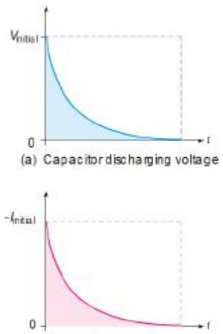
When a capacitor is charged through a series resistor and dc source, the charging curve is exponential.



Summary: Capacitors in dc circuits (2 of 2)

When a capacitor is discharged through a resistor, the discharge curve is also an exponential. (Note that the current is negative.)





(a) Capacitor discharging voltage

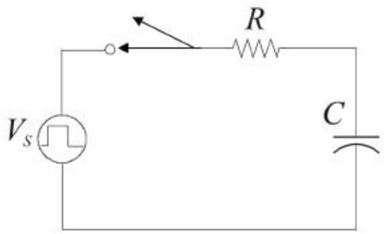
(b) Discharging current

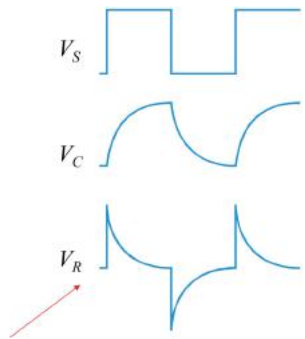
Summary: Capacitors in dc circuits

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

Question

What is the shape of the current curve?





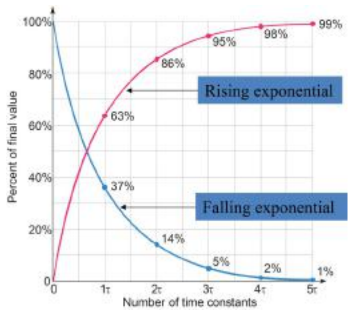
The current has the same shape as V_R.

Summary: Universal exponential curves (1 of 2)

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

$$\tau = RC$$

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



Summary: Universal exponential curves (2 of 2)

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

$$v = V_F + (V_i - V_F)e^{-t/RC}$$

V_F = final value of voltage

V_i = initial value of voltage

v = instantaneous value of voltage

The final capacitor voltage is greater than the initial voltage when the capacitor is charging, or less that the initial voltage when it is discharging.

Summary: Capacitive reactance

Capacitive reactance is the opposition to ac by a capacitor. The equation for capacitive reactance is

$$X_C = \frac{1}{2\pi fC}$$

Example

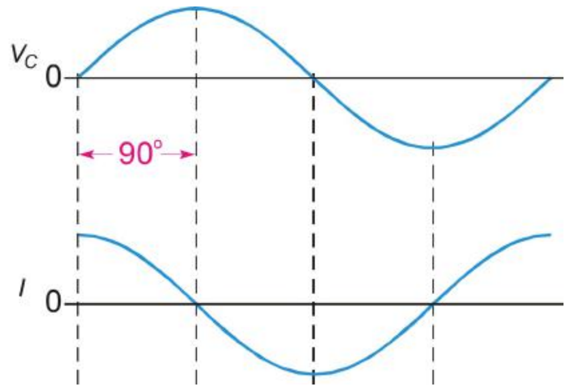
The reactance of a 0.047 μF capacitor when a frequency of 15 kHz is applied is $X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi(15\text{ kHz})(0.047\ \mu\text{F})} = 226\ \Omega$

Question

For the 0.047 μF capacitor, at what frequency is the capacitive reactance = 1.0 kΩ? 3.39 kHz

Summary: Capacitive phase shift

When a sine wave is applied to a capacitor, the phase shifts such that the current always leads the voltage by 90°.



Summary: Power in a capacitor

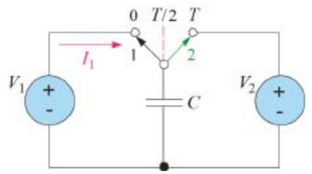
Energy is stored by the capacitor during a portion of the ac cycle and returned to the source during another portion of the cycle.

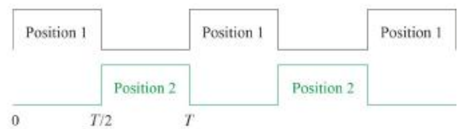
Voltage and current are always 90o out of phase. For this reason, no true power is dissipated by a capacitor, because stored energy is returned to the circuit.

The rate at which a capacitor stores or returns energy is called **reactive power**. The unit for reactive power is the VAR (volt-ampere reactive).

Summary: Switched capacitors

Switched capacitors move charge in a specific time interval between two points that are different voltages. The switched capacitors effectively limit current, hence they emulate a resistor with a value of $R=1/(fC)$. Switched capacitors are widely used in certain types of integrated circuits because they can be made very small, have virtually no drift, and do not dissipate heat.





Selected Key Terms (1 of 2)

Capacitor An electrical device consisting of two conductive plates separated by an insulating material and possessing the property of capacitance.

Dielectric The insulating material between the conductive plates of a capacitor.

Farad The unit of capacitance.

RC time constant A fixed time interval set by the R and C values, that determine the time response of a series RC circuit. It equals the product of the resistance and the capacitance.

Pearson

Selected Key Terms (2 of 2)

Capacitive reactance The opposition of a capacitor to sinusoidal current. The unit is the ohm.

Instantaneous power (p) The value of power in a circuit at a given instant of time.

True power (P_{true}) The power that is dissipated in a circuit usually in the form of heat.

Reactive power (P_r) The rate at which energy is alternately stored and returned to the source by a capacitor. The unit is the VAR.

VAR (volt-ampere reactive) The unit of reactive power.

Pearson

Quiz (1 of 11)

1. The capacitance of a capacitor will be larger if
   a. the spacing between the plates is increased
   b. air replaces oil as the dielectric
   c. the area of the plates is increased
   d. all of the above

Pearson

Quiz (2 of 11)

2. The major advantage of a mica capacitor over other types is
   a. they have the largest available capacitances
   b. their voltage rating is very high
   c. they are polarized
   d. all of the above

Pearson

Quiz (3 of 11)

3. Electrolytic capacitors are useful in applications where
   a. a precise value of capacitance is required
   b. low leakage current is required
   c. large capacitance is required
   d. all of the above

Quiz (4 of 11)

4. If a 0.015 μF capacitor is in series with a 6800 pF capacitor, the total capacitance is
   a. 1568 pF
   b. 4678 pF
   c. 6815 pF
   d. 0.022 μF

Quiz (5 of 11)

5. Two capacitors that are initially uncharged are connected in series with a dc source. Compared to the larger capacitor, the smaller capacitor will have
   a. the same charge
   b. more charge
   c. less voltage
   d. the same voltage

Quiz (6 of 11)

6. When a capacitor is connected through a resistor to a dc voltage source, the charge on the capacitor will reach 50% of its final charge in
   a. less than one time constant
   b. exactly one time constant
   c. greater than one time constant
   d. answer depends on the amount of voltage

Quiz (7 of 11)

7. When a uncharged capacitor is connected through a series resistor and switch to a dc voltage source, the voltage across the resistor after the switch is closed 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. The capacitive reactance of a 100 μF capacitor at 60 Hz is
   a. 6.14 kΩ
   b. 265 Ω
   c. 37.7 Ω
   d. 26.5 Ω

Quiz (9 of 11)

9. If an sine wave from a function generator is applied to a capacitor, 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 (10 of 11)

10. A switched capacitor emulates a
    a. smaller capacitor
    b. larger capacitor
    c. battery
    d. resistor

Quiz (11 of 11)

Answers:

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