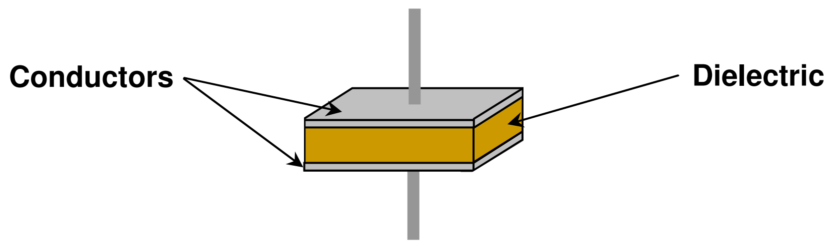
CAPACITOR BASICS I – How Capacitors Work

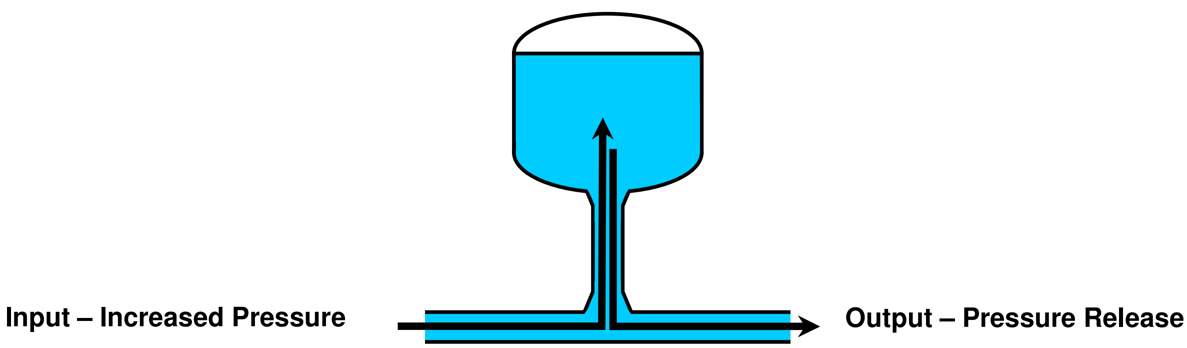
The Basic Capacitor

A capacitor is an electrical device which serves to store up electrical energy for release at a predetermined time. In its most basic form, it is comprised of three essential components, two (2) metal plates or conductors, separated and insulated by the third part called the dielectric. A capacitor should not be confused with a battery inasmuch as both devices store energy, but unlike a battery that relies on a chemical reaction to generate electrons, a capacitor can't produce electrons, it can only store them.



The Basic Capacitor

In simple terms a capacitor can be compared to a water tower. A water tower stores water when the water system produces more water than the user can consume and this water pressure can be released and flow out of the tower during periods of higher demand. Using the same analogy, a capacitor stores electrons instead of water and releases this energy when required at a later time.



Water Tower / Capacitor Analogy

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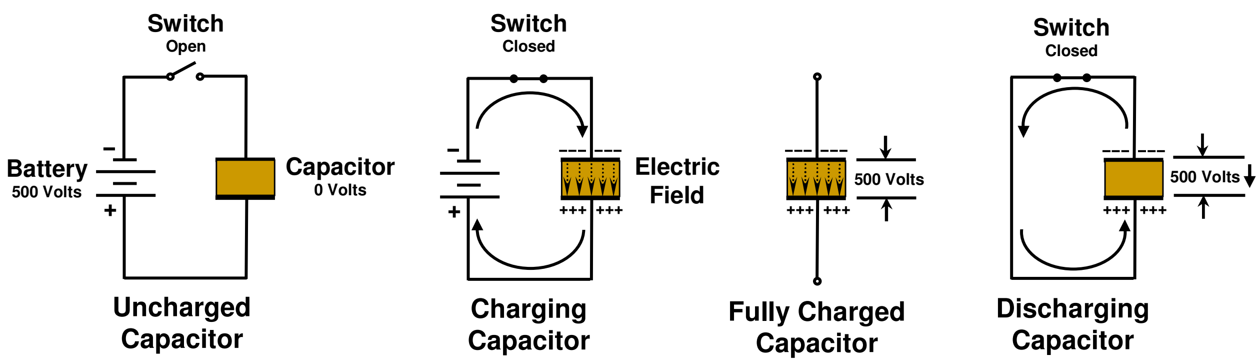
Charging and Discharging an Ideal Capacitor

As voltage is applied to the conductors of a capacitor an electric field is established between the conductors and an electric charge of equal and opposite value starts to accumulate on these plates. This charge will continue to build up until the voltage potential across the capacitor equals the voltage level of the source. It is important to note that current does not in fact flow through the dielectric. Rather the capacitor exhibits an electron depletion condition whereby an electron accumulates on the negative plate for every one that leaves the positive plate.

Dielectrics are insulators and as such they cannot conduct energy. Consequently, if the voltage source were now disconnected, the electric field would still exist between the plates and the capacitor would maintain the charge across its dielectric for and indefinite period of time.

If the voltage source were now replaced by a low resistance path, the negative plate of the capacitor would repel the stored electrons which in turn would be attracted to the positive plate until such time as all of the negative and positive electrons are neutralized. Once the discharge cycle is complete the capacitor is returned to its original condition, whereby no net charge remains and the voltage across it equals zero. If a voltage source were again connected to the capacitor the same sequence would be repeated.



Charge / Discharge Sequence for Ideal Capacitor

Energy Storage

If we were to assume that the geometry of the capacitor were fixed then we can correlate the amount of charge that the capacitor can store to the size of the capacitor and the amount of pressure or voltage that is applied. This relationship can be expressed by the following formula:

$$Q = CV$$

Where Q = Electric Charge (Coulombs)
C = Capacitance Value (Farads)
V = Applied Voltage (Volts)

Work must be done by an external stimulus to generate this charge between the conductors and as shown before when this external influence is removed, the charge separation continues to persist in the electric field and energy is stored until such time as the charge is allowed to return to its original state of equilibrium. The work done to establish the electric field and the amount of energy stored is given by the formula:

$$W = \int_{Q=0}^{Q} V \cdot dQ = \int_{Q=0}^{Q} \frac{Q}{C} \cdot dQ = \frac{1}{2} \bullet \frac{Q^2}{C} = \frac{1}{2} \bullet VQ = \boxed{\frac{1}{2} \bullet CV^2}$$

Where W = Energy Stored (Joules)
Q = Electric Charge (Coulombs)
V = Applied Voltage (Volts)
C = Capacitance Value (Farads)

Basic Applications

It is this basic ability of a capacitor to store energy for controlled release that makes it an extremely valuable tool for use in a wide range of applications in the electronics industry. Typical applications would include:

- **Energy / Pulse Discharge** - The energy stored in the capacitor can be discharged for use in an ignition, firing or triggering circuit or as a power source.
- **Direct Current Blockage** – Once fully charged a capacitor acts as a high impedance device and can block the passage of DC current while still allowing AC current to pass to a specified portion of the circuit.
- **Coupling of Circuit Components** – With the ability to pass AC signals, a capacitor has the capacity to couple one section of an AC circuit to another circuit.
- **Decoupling of Circuit Components** – Capacitors are often used in integrated circuits (IC’s) to minimize noise in the logic signal by providing an additional current source.
- **Filter Capacitors** – The reactance of a capacitor is inversely proportional to the frequency thereby offering decreased resistance to current flow at higher frequency levels. This ability to decrease or increase the impedance of the circuit allows the capacitor to discriminate and filter out undesired frequencies.
- **By-Pass Capacitor** – The ability to block DC current and allow the passage of AC current permits the capacitor to be placed in parallel with other components to by-pass the AC at a certain frequency without allowing the DC component of the signal to pass.
- **Snubber Capacitors** – Capacitors can be used to protect sensitive components in a circuit by limiting the energy associated with high voltage transients generated by the opening of relays or silicon controlled rectifiers (SCR) used to drive high inductance loads.

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Units of Measure

As indicated above, the unit of measure for capacitance is farad (F) and the International System of Units (SI) defines one (1) farad as a unit of capacitance equal to that of a capacitor carrying one (1) coulomb of charge when a potential difference of one (1) volt is applied.

In actuality 1 farad is considered to be an extremely large unit of measurement and in general terms this value would not be practical for the majority of applications where capacitors are used. Yes, in applications where electrolytic capacitors, super or ultra capacitors and capacitor banks are employed this unit of measurement would warrant consideration, but in the larger majority of designs much smaller capacitance values dictate the use of fractional multiples, namely:

microfarad (µF) $= 1 \times 10^{-6}$ farad
nanofarad (nF) $= 1 \times 10^{-9}$ farad
picofarad (pF) $= 1 \times 10^{-12}$ farad

Factors Affecting Capacitance

As indicated earlier, capacitors are comprised of three basic components, a dielectric material and two (2) metal conductors and the amount of capacitance that can be achieved is highly dependant on the physical and / or electrical properties of these components.

Dielectrics can be comprised of either a solid, a liquid or a gas and for certain capacitors, a combination of these. With all else being equal, the type of dielectric used can have a significant impact on the value of capacitance. Every dielectric material is assigned a dielectric constant (K) or relative permittivity (ε_r) and this constant value represents the ratio of capacitance that can be achieved in a capacitor using that dielectric material compared to a similar capacitor that uses air in a vacuum as its dielectric. Common dielectric materials and their corresponding K values or ε_r are shown in Table I.

Dielectric Material	Dielectric Constant (K value)	Dielectric Material	Dielectric Constant (K value)
Air (vacuum)	1	Mica / Epoxy	4 - 9
Air (1 atm)	1.00059	Paper / Mineral Oil	1.5 - 3
Alumina	9	Polyester	3.1 - 3.3
Aluminum Oxide	7 - 10	Polypropylene	2.1 - 2.3
Distilled water	80	Tantalum Oxide	24
Glass Epoxy (FR4)	4.4 - 4.7	Teflon	2.1
Graphite	10 - 15	Titinate Ceramic	15 - 22000

Table I – Common Dielectrics / K Values @ +20ºC

Adjusting the size of the metal conductors will change the overall contact area between the plates and the dielectric material and will also impact the amount of capacitance that can be achieved. A larger plate area for example, enlarges the size of the electric field thru the dielectric and increases the amount of charge that can be stored. Consequently, although the potential difference across the capacitor remains the same, the amount of capacitance will change in proportion to the area of metal plates.

Finally, adjusting the distance between the metal plates will also impact the amount of charge that can be stored within a capacitor. With the potential difference fixed, decreasing the dielectric thickness will increase the flux density of the electric field and vice versa. Consequently, for a specific dielectric material and plate size, the capacitance value of the device is found to be inversely proportional to the distance between the metal plates.

The relationship between dielectric type, dielectric thickness and plate size is expressed by the following formula:

$$C = f \bullet \frac{K \bullet A}{t}$$

Where C = Capacitance (picofarads)
f = Conversion factor (0.2246 for English system of units or 0.0884 for Metric units)
K = Dielectric Constant for material used
A = Area of electrode that overlaps adjacent electrode (inch^2 or centimeter^2)
t = Thickness of dielectric (inch or centimeter)

Example 1:

Determine the capacitance value for an X7R capacitor with a dielectric constant of 1600 that is 1.000” long by 0.500” wide and has a dielectric thickness of 0.200”.

C = f x (K x A) / t
= 0.2246 x (1600 x 1.000” x 0.500”) / 0.200”
= 898 pF

Example 2:

Determine what plate area would be required to meet a capacitance value of 10,000 pF, using a dielectric with K value of 1600 and a dielectric thickness of 0.200”.

A = (C x t) / (f x K)
= (10000 x 0.200”) / (0.2246 x 1600)
= 5.566 in^2

For additional information on Capacitor Basics, please refer to subsequent Application Notes AN109-2, “Capacitor Types” and AN109-3, “Mechanical Configurations”, or contact CalRamic Technologies, LLC with your questions. We are always here to help!

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