Why Capacitors Do What They Do

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Technologies LLC

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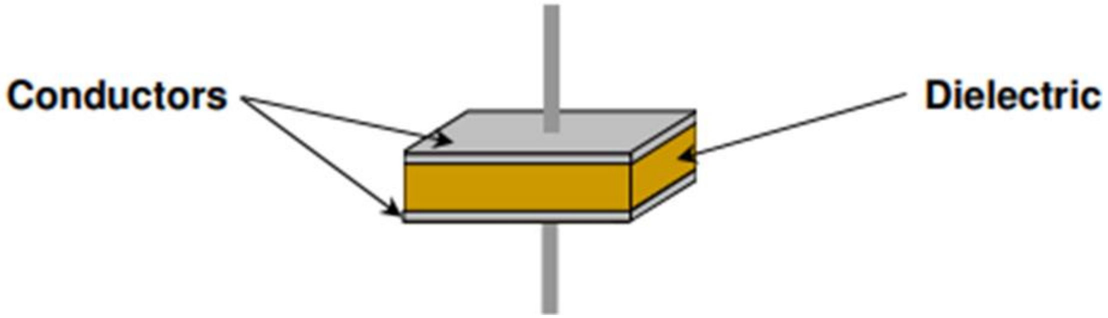
Topics of Discussion

- Capacitor Basics
  - Capacitor Definition
  - Fundamental Structure
  - Generating Capacitance
  - The Simple Capacitor
  - Increasing Capacitance Value
  - Capacitance & Charge
  - Energy Density
  - Capacitor Equivalent Circuit
  - Impedance
  - Resonance Frequency
  - Heat Loss
  - Ragone Plot
  - Discharge Curves
  - Quality Control
- Batteries Vs Capacitors
- Phase Angles
- Applications
- Summary

Capacitor Definition



A capacitor is defined as a device that stores energy. Simply stated, when one joule of energy is put into an ideal capacitor, one joule of energy can then be removed from that capacitor as required. The reason for this is that the energy put into the capacitor is stored in an electrostatic field.

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Capacitor Basics

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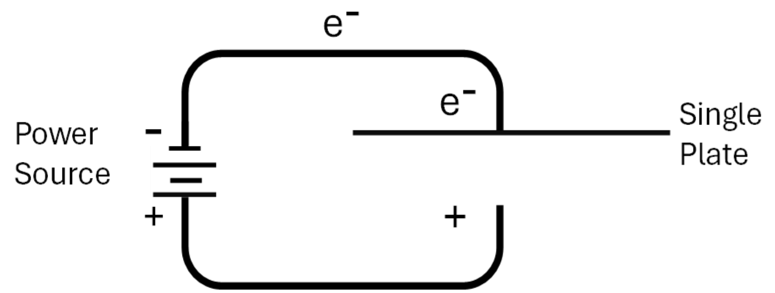
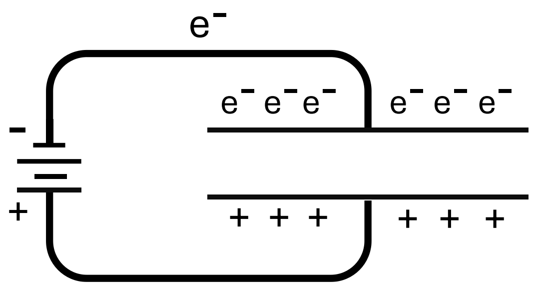
Fundamental Structure



Having a power source hooked up to a single plate (conductor) does not make a capacitor.



An opposing plate (conductor) is needed to create an electrostatic field which provides capacitance

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Capacitor Basics

Generating Capacitance

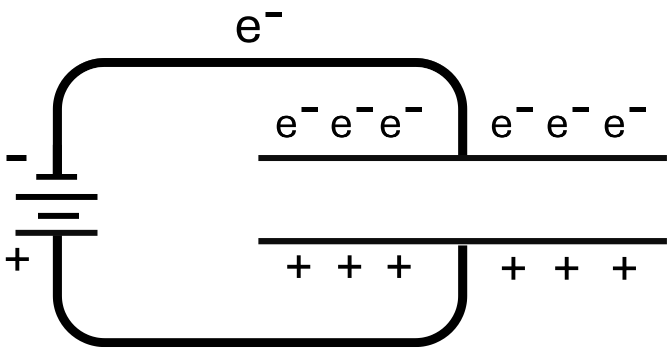
Electrons don’t like each other.

Electrons trying to stay away from each other determines:

- How a capacitor stores energy
- How a capacitor charges
- How a capacitor discharges
- How current is knocked out of phase with voltage

Capacitor Basics

The Simple Capacitor



Electrons see the positive plate on the other side. They want to get over there and are willing to bunch up to try and get to the other side

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Capacitor Basics

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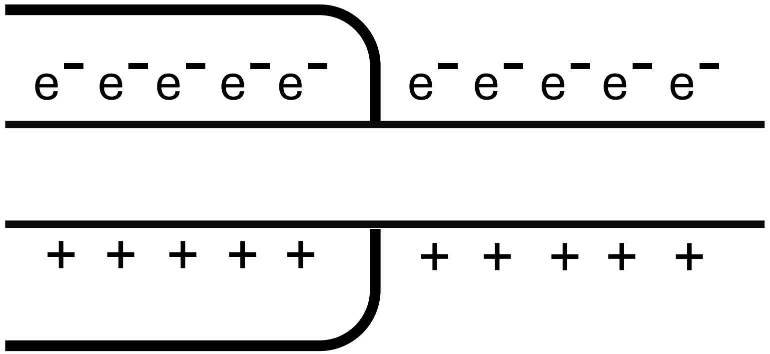
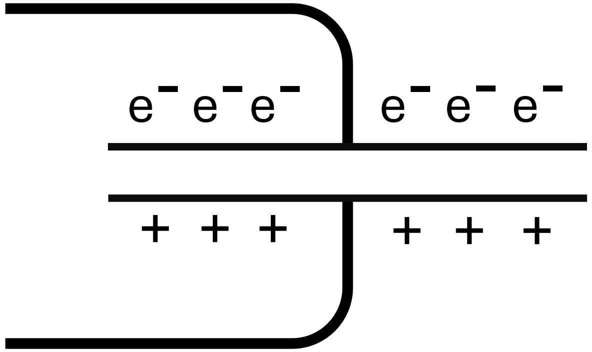
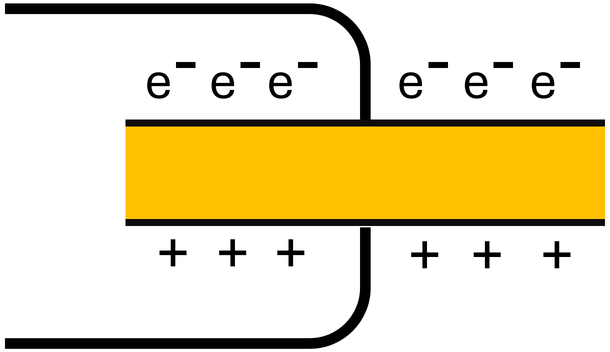
Increasing Capacitance Value



Increase the Plate Area

Decrease the distance
between Plates





Add an Insulator (Dielectric)
Between The Plates

Capacitor Basics

Capacitance & Charge (Q / e^-)

$$C = K_oK \times \frac{A}{t} \quad \text{(Measured in Farads)}$$

Where K_o = Permittivity of Free Space K = Dielectric Constant
A = Area t = Dielectric Thickness

But you need voltage in order to generate a charge

$$Q = CV \quad \text{(Measured in coulombs)}$$

Where Q = Charge C = Capacitance V = Voltage

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Capacitor Basics

Calculating Electron Charge (e^-)

- Basic capacitor rated for 1 F @ 1 V

  $Q = CV = 1\ \text{F} \times 1\ \text{V} = 1\ \text{F}\cdot\text{V}$

  $F = \text{A}\cdot\text{sec} / \text{V}$ So $Q = 1\ \text{A}\cdot\text{sec} / \text{V} \times \text{V} = 1\ \text{A}\cdot\text{sec}$

  $A = 6.24 \times 10^{18}\ e^- / \text{sec}$

  $Q = (6.24 \times 10^{18}\ e^- / \text{sec}) \times \text{sec} = 6.24 \times 10^{18}\ e^-$

Therefore, there are 6.24×10^{18} electrons capable of doing work

- CalRamic SMPS3BR106K201NS480 rated for 10 µF @ 200 V

  $Q = 0.00001\ \text{F} \times 200\ \text{V} = 0.002\ \text{A}\cdot\text{sec}$

  $= 0.002 \times 6.24 \times 10^{18} = 1.25 \times 10^{16}$ e-

Therefore, there are 1.25×10^{16} electrons capable of doing work

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Capacitor Basics

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Energy Density (E)

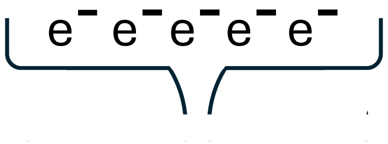
$$E = \tfrac{1}{2}CV^2$$

Say we have two capacitors: 5 F at 1 V and 1F at 5 V

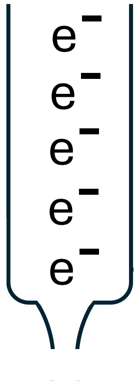
Q for both is 5 coulombs

Energy of 5 F at 1 V: $E = \tfrac{1}{2}\, 5 \cdot 1^2 = 2.5$ joules

Energy of 1 V at 5 F: $E = \tfrac{1}{2}\, 1 \cdot 5^2 = 12.5$ jouleS



5 F at 1 V
2.5 joules



1 F at 5 V
12.5 joules

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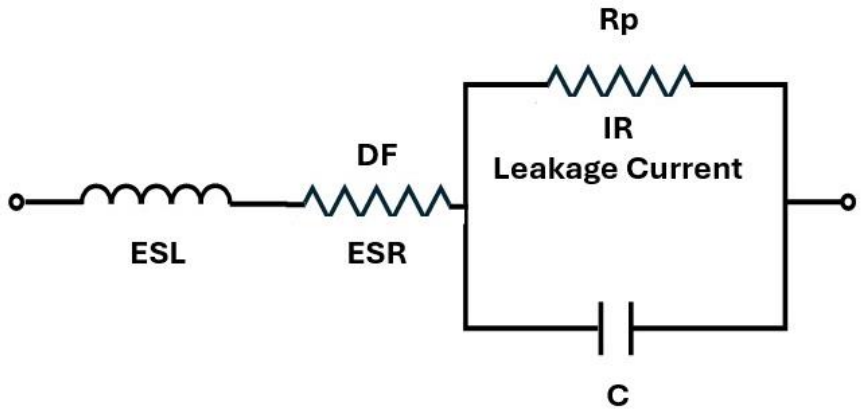
Capacitor Basics

Capacitor Equivalent Circuit

- No capacitor is perfect and exhibits losses
- This can be represented by an equivalent circuit outlining how a capacitor behaves

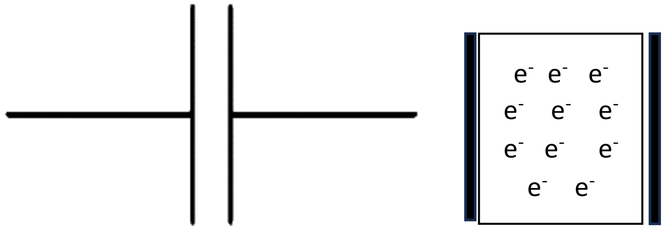


Where:
ESL = Equivalent Series Inductance
ESR = Equivalent Series Resistance
DF = Dissipation Factor
IR = Insulation Resistance
Rp = Parallel Resistance
C = Capacitance

Capacitor Basics

Equivalent Circuit Components

Electrostatic Field



Capacitor

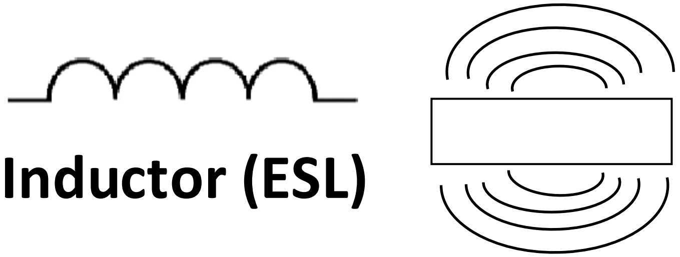
Energy put into a capacitor is stored in an electrostatic field.

Heat

Resistor (ESR)

Energy put into a resistor is converted to heat.

Magnetic Field



Inductor (ESL)

Energy put into an inductor creates a magnetic field.

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Capacitor Basics

Resonance Frequency (f_R)

The resonance frequency, f_R is the frequency at which a capacitor is no longer behaving as a capacitor and starts to display inductive behavior.

At f_R the capacitive reactance (X_C) and inductive reactance (X_L) cancel each other out and the impedance of the capacitor is the same as the ESR.

$$\text{Impedance} = Z = \sqrt{ESR^2 + (X_C - X_{ESL})^2}$$

$$X_C = 1 / (2\pi f \times C) \qquad \& \qquad X_{ESL} = 2\pi f \times ESL$$

$$\text{At } f_R \qquad X_C = X_{ESL}$$

$$f_R = \frac{1}{2\pi * \sqrt{C * ESL}}$$

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Capacitor Basics

Calculating Heat Loss With DF & ESR Loss

$$V \times I \times DF = I^2 \times ESR = \text{Watts (heat loss)}$$

$$DF = \%$$

$$ESR = \text{ohms } (\Omega)$$

$$DF = ESR \times 2\pi fC$$

Capacitor Example

PD4040CRO9164K142S Disc rated at 0.16µF at 1400 VDC

Measured @ 1 kHz:

Measured C = 153 nF / DF = 0.00071 / ESR = 0.74 Ω

Verification:

$$DF = ESR * 2\pi f * C$$

$$DF = 0.74 * 2\pi * 1000 * 0.000000153$$

$$DF = 0.00071$$

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Calculating Heat Loss @ 1000 VAC

Calculating Heat Loss Using ESR and DF Loss Characteristics

Heat loss $= (2\pi fCV)^2 * \text{ESR}$ (For ESR we use I^2R)

$= (2\pi * 1000 * 0.000000153 * 1000)^2 * 0.74$

$= 0.683$ Watts

Heat loss $= 2\pi fC * V^2 * \text{DF}$ (For DF we use DF * VAR)

$= (2\pi * 1000 * 0.000000153) * 1000^2 * 0.00071$

$= 0.683$ Watts

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Dissipation Factor (DF) Explained

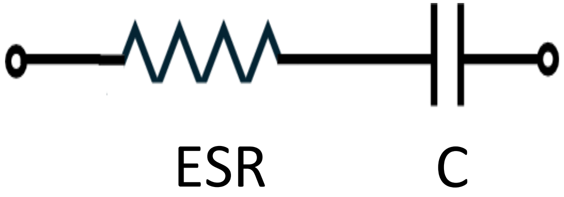
Simple Explanation of DF

- In simple terms …. DF and ESR are both loss characteristics and are directly proportional

- DF is the percentage of heat generated by the capacitor

- As an example...
  - If a capacitor has a DF of 1% and we put 100 joules of energy into the capacitor then 99 joules comes back out as usable and 1 joule is lost and converted to heat

ESR Affect On Pulse Discharge



τ (Time Constant) = RC

5τ is the amount of time in seconds that it takes for a capacitor to be considered fully discharged

5τ = 5 * (ESR x C)

By comparison, a ceramic capacitor exhibits significantly lower ESR characteristics than a similarly rated electrolytic capacitor. This improvement in efficiency should allow the engineer to replace an electrolytic capacitor with a lower capacitance rated ceramic capacitor in switching power supply applications and achieve the same performance as the electrolytic.

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Quality Control

Important Considerations

Capacitance, Dissipation Factor (DF) / Equivalent Series Resistance (ESR) & Insulation Resistance (IR) tests are utilized for quality control.

Through experience, we know what these values should be:

- If DF / ESR readings are higher than normal and / or IR is lower than normal, than we know that something is wrong with the capacitor

Even if capacitor readings are within spec and the capacitor appears to be behaving normally, DF, ESR or IR readings that are out of population with the lot may be indicative of an issue with that specific unit which in turn may cause concern over the possibility of introducing a latent failure condition.

Parasitics

Parasitics are unwanted properties that play a significant role in the capacitor selection process. They are inherent in the dielectric material or exist as a result of construction design.

Parasitics:

- DF/ESR
- ESL
- Insulation Resistance (IR) / Leakage Current
- Hysteresis
- Partial Discharge (Corona)

Properties:

- Temperature Dependent Capacitance
- Voltage Dependent Capacitance

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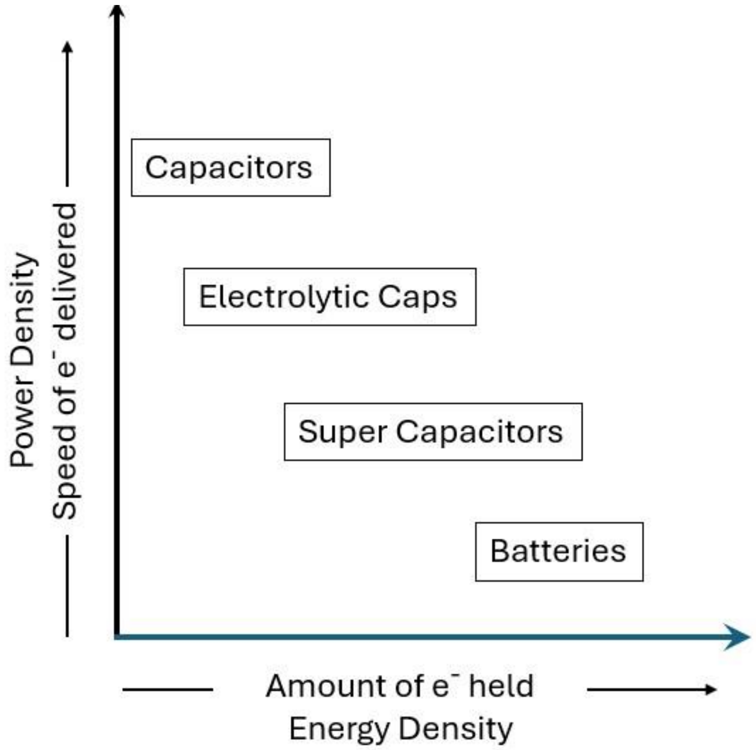
Capacitor Basics

Ragone Plot



Capacitors

Electrolytic Caps

Super Capacitors

Batteries

Power Density

Speed of e^- delivered

Amount of e^- held

Energy Density

By comparison Capacitors have a higher power density and are capable of delivering electrons faster Vs other energy sources which exhibit a lower power density and deliver electrons over a more extended period of time

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Capacitors Vs Batteries

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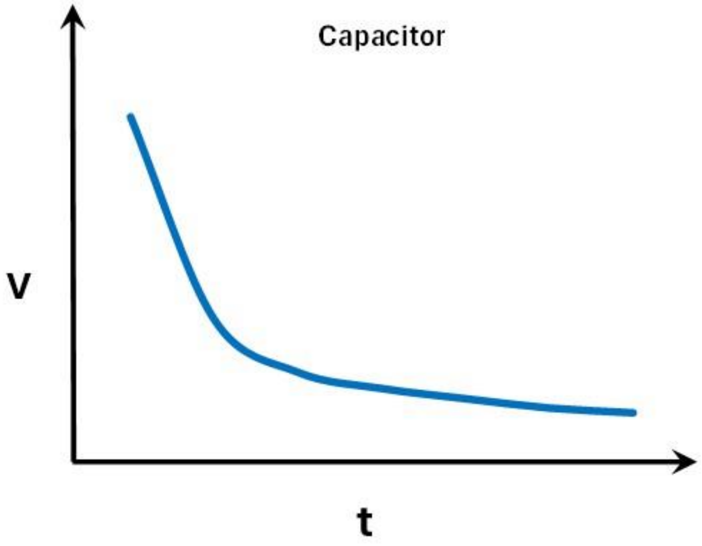
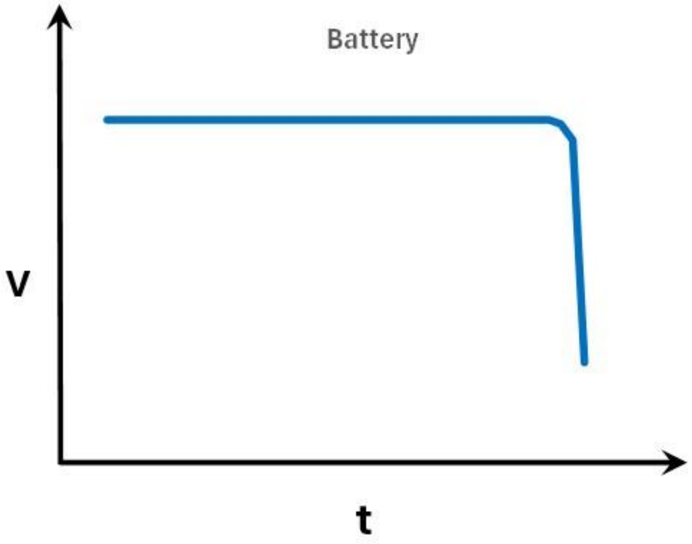
Discharge Curves



$$V = V_0 e^{\frac{-t}{RC}}$$



V generally remains steady until end of life

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Capacitors Vs Batteries

Energy of a Capacitor Vs a Battery

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Energy of a CalRamic SMPS3BR106K201NS480 Capacitor

Rated for 10 µF @ 200 V

$$E = \tfrac{1}{2}CV^2$$

$$= \frac{0.00001 \times 200^2}{2} = 0.2 \text{ joules}$$

Energy of a AA Battery

Rated for 2.5 Ah @ 1.5 V

E (Watts) = Ah x V

E = 2.5 Ah x 1.5 V = 3.75 Watts

1 Ah = 3600 Asec

Therefore 3.75 Watts x 3600 = 13,500 joules

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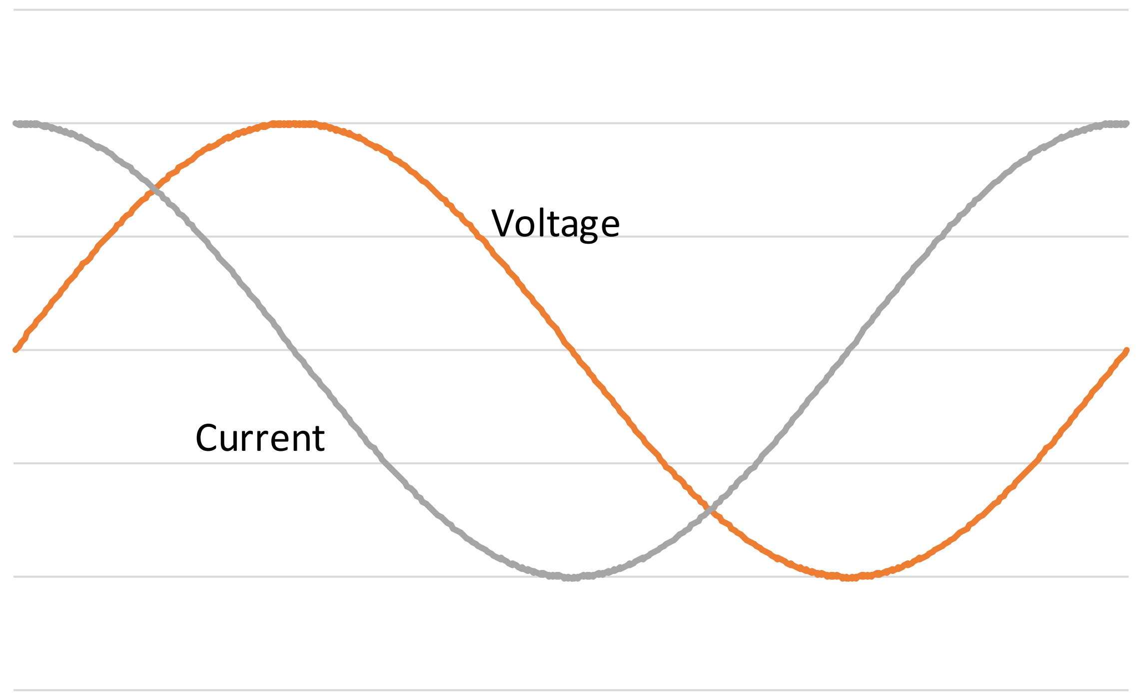
Capacitors Vs Batteries

Fundamental Differences

- A battery is not a capacitor & a capacitor is not a battery
- A battery is a chemical device & a capacitor is a passive device with no chemical reaction
- To charge a capacitor to 10 V we set the power supply to 10 V
- To charge a 12.5 V car battery, we need to set the power supply to 14.5 V in order to reverse the chemical reaction
- A capacitor offers a much higher power density than a battery and a battery offers a much higher energy density than a capacitor
- A capacitor can be just as important discharged vs charged

Phase Angles



- Current is out of phase by 90 degrees with voltage in a capacitive circuit
- When voltage is zero, electrons see an empty space and will flow readily into the capacitor and slow gradually as the capacitor charges
- This is an important concept in applications like Power Factor Correction where current is brought back into phase caused by inductive loads

Capacitor Types

Over a trillion discreet capacitors are made a year.

- Ceramics
- Film
- Aluminum Electrolytic
- Tantalum Electrolytic
- Solid Electrolytic
- Niobium Electrolytic
- Super Capacitors
- Paper / Oil Filled
- Mica
- Air
- Glass

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Capacitor Selection

Parameters:

- Voltage Rating
- Capacitance
- Max/Min Temperature
- Environment
- Shock and Vibration
- Capacitance Stability
- Mode of Failure
- Energy Density
- Power Density
- Ripple Current
- Peak Current
- Operating Frequency
- Resonance Frequency
- Polarity
- COST

Parasitics:

- ESR / DF
- ESL
- IR / Leakage Current
- Corona / Partial Discharge
- Hysteresis

Properties:

- Temperature Coefficient
- Voltage Coefficient

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Ways A Capacitor Can Be Used

Function	Application
Energy Storage	• Battery Replacement
Pulse Discharge	• Detonator • Aircraft Carrier Launcher • Laser • Radar
Voltage Stabilization	• Hold Up • Reservoir • Snubber • Smoother • Switch Mode • DC Link
Phase Shifting	• Motor Run • Power Factor Correction
Filtering - Multiple Frequencies	• DC Blocking • AC Coupling • Safety Capacitors - X Cap / Y Cap • Low Pass Filter • High Pass Filter • Band Pass Filter

Why Capacitors Do What They Do...

Summary

- Capacitors are passive electronic devices
- Simple in concept but complex in behavior
- No capacitor is perfect
- A capacitor is not a battery, and a battery is not a capacitor
- Capacitors are an integral part and essential component in almost all aspects of today’s technological world

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