Capacitors
Basics &
Applications

Applications - I
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Capacitors & Applications

Ceramic Tantalum Alum. Elect. Film
All capacitors utilize the same basic mechanism in their structure.

Electrode Plates ➔ Dielectric

The value of a capacitor is measured in farads. For 1 farad of capacitance, 1 coulomb of charge is stored on the plates, when 1 volt of force is applied.

1 farad = 1 coulomb / 1 volt

1 coulomb represents ~ 6 x 10^{19} electrons
"Pure" Capacitor

\[ Z = X_C = \frac{1}{2\pi f \, \text{(Hertz)} \, C \, \text{(Farads)}} \]
“Pure” Capacitor’s Performance

Impedance (Ohms)

Frequency (Hz)

0.0001
0.001
0.01
0.1
1
10
100
1000
10000
100000
1,000,000
10,000,000

0.47 uF
4.7 uF
47 uF
Capacitor with Series Resistance

\[ |Z| = \sqrt{X_C^2 + ESR^2} \]
Impedance, Reactance, and Resistance are Vectors

Impedance

$Z$ is complex, containing both real and imaginary coefficients, or magnitude and angle (direction).

Resistance

(ESR) is "Real Element"

Reactance

$(\bar{X}_L + \bar{X}_C)$ is imaginary

$$|Z| = \sqrt{X_c^2 + ESR^2}$$
Capacitance & Resistance vs. Freq.

Capacitance with ESR vs. Frequency

Impedance (Ohms)

Frequency (Hz)

47, 4.7, and .47 uF
ESR = 1 and 0.1 ohms

1.0 Ohm ESR

0.1 Ohm ESR
High Frequency or Tuned Circuit Applications

Q

Power Applications

ESR

General Applications

DF
Based on Vector relationship

\[ DF = \cot(\Theta) = \frac{ESR}{X_c} \]
\[ PF = \cos(\Theta) = \frac{ESR}{Z} \]
\[ Q = \tan(\Theta) = \frac{X_c}{ESR} = \frac{1}{DF} \]

where
- \( DF \) = Dissipation Factor
- \( PF \) = Power Factor
- \( Q \) = "Q" or figure of merit
ESL or Equivalent Series Inductance is created by restricting current to a defined, physical path.
ESL - Inductive Reactance ($X_L$) opposes Capacitive Reactance

Impedance is a factor of vector summation.

$$\vec{Z} = \vec{X}_C + \vec{X}_L + \vec{R}$$

or

$$|Z| = \sqrt{(|X_C| - |X_L|)^2 + |R|^2}$$
The frequency at which $X_C = X_L$ is the self-resonant frequency. At this frequency, $X_C = -X_L$, or zero, and the impedance is equal to the ESR.

Prior to this frequency, the component behaves as a capacitor; after this frequency, the component behaves as an inductor.

$$f = \frac{1}{2\pi\sqrt{LC}}$$
47 uF Capacitance / 2.5 nH ESL
Impedance versus Frequency versus ESR

Impedance (Ohms)

Frequency (Hz)
Ceramic vs. Tantalum (4.7 uF)

- Ceramic Z
- Tantalum Z

Impedance/ESR (Ohms)

Frequency (kHz)

- Ceramic ESR
- Tantalum ESR
Impedance across types

Lowest Impedance is not always highest Capacitance

Impedance (Ohms)

100 uF
Aluminum

10 uF
Tantalum

1 uF
Ceramic

Frequency (kHz)
Capacitance change with frequency

- Film: -2% to -5%
- Ceramic: 0% to -5%
- Aluminum: -15% to -90%
  ~10kHz to 30kHz
- Tantalum: -15% to -60%
  ~30kHz to 300kHz
Actual capacitance change - measured

4.7 uF Tantalum vs. Ceramic
T491B475K010 vs. C700 Z5U 50 WVDC
Capacitance vs. Frequency
Meter determines capacitance or inductance based on dominant reactive element, with no consideration for any recessive trait.
Measuring with pure sinusoidal signal

Most equipment measures phase and amplitude resultants from sinusoidal source.
Dynamic – Current Pulse Injection

Constant Current Level

0 Current Level

Transition Time
Voltage Response (from current pulse)

**Pure Resistor**
- **0 Current Level**
- **Constant Current**
- **Transition Voltage**
- **Constant Voltage Level**
- **Transition Time**
- **0 Voltage**

**Pure Capacitor**
- **0 Current Level**
- **Constant Current**
- **Voltage Increasing Exponentially**
- **0 Voltage Level**
- **Transition Time**

**Pure Inductor**
- **0 Current Level**
- **Constant Current**
- **Transition Voltage**
- **Voltage Decays to 0 "Rings out"**
- **0 Voltage**
- **Transition Time**
Pulse response is complex, combining capacitive, inductive, and resistive voltages.

\[
C = \frac{I_{\text{Constant}} \times (t_2 - t_1)}{(v_2 - v_1)}
\]

\[
V_{C(\text{tr})} = \frac{I_{\text{Const}}}{C} \times \frac{tr}{2}
\]
Decaying Slope of Electrolytics

Slope is decaying

Typical Electrolytic

Typical Ceramic

Volts

Time
Derived capacitance from $dv/dt$ Slope

**Capacitance vs. Time**

- **Ceramic X7R 10 μF**
- **Ceramic X7R 4.7 μF**
- **Solid Ta "Low ESR" 5.6 μF**
- **Wet Ta 10 μF**
- **Al Electrolytic Low Profile 15 μF**

**Time (nSec.):**

- 1
- 10
- 100
- 1,000
- 10,000

**Capacitance (μF):**

- 0
- 2
- 4
- 6
- 8
- 10
- 12
- 14
- 16
- 18
Decaying Voltage on Decoupling Caps

Volts

Initial Level

Typical Ceramic

Typical Electrolytic

Time
Capacitance & ESR

- 1µF-1,000µF Comm. T491/T494 MnO₂
- 4.7µF-1,000µF Low-ESR T495 MnO₂
- 15µF-1,000µF T520 Ta-Poly
- 8.2µF-470µF A700 Al-Poly
- 330µF-1,500µF T510 MA
- 220µF-1,500µF T530 MP
- 1µF-47µF Ceramic

Capacitance (µF)
Applications: "grandfather" controlled.

- Power Applications
- Small Signal Processing
  - (Decoupling, Bypass, Coupling)
- Large Capacitance
  - (Power Entry, low Current Hold-Up, low Frequency Bypass)
- Small Capacitance
  - High Freq., High Current
    (Oscillator, High Frequency Bypass)
- Aluminum
- Film, Ceramic
- Tantalum
- Film
Main Areas of Application

- Decoupling
- Filtering
- Coupling
- Timing / Wave Shaping
- Oscillating
One of the first characteristics of capacitors:

*The capacitor allows an AC signal to pass, but stops DC.*

- **Requirements**
  - May have to handle wide frequency range
  - Must not cause large, unexpected phase shifts
  - May have to handle large currents
  - Capacitance stability not critical
  - Noise from capacitor critical
By utilizing an exaggerated RC charge scheme, the subsequent functioning of a succeeding circuit can be manipulated to a controlled delay function of the RC constant.

Common experience can be found with:
- Vertical Sweep circuits in TV and computer monitors
- Delay wipers in automobiles
- Here the resistor is varied to allow the cap to charge quickly or at a slow rate

Timing circuits require fairly stable components. Many timing circuits are being replaced with digital counters.
Trying to satisfy all needs from a central-sourcing location

Monday - back from vacation - don’t want to get up.
In shower water perfect temperature.
Ahhhh! I need 5 minutes!

Central Water Supply / Source

Shower  Toilet  Sink  Clothes Washer  Dish Washer
Suddenly a disturbance!

Someone (devilish), sleepy eyed flushes the toilet!

Yaugh!!

Suddenly TOO HOT!!
or TOO COLD!!

Shower  Toilet  Sink  Clothes Washer Starts!!  Dish Washer Starts!!
Secondary supplies act as intermediaries back to central source.
Water decoupling in Taipei
Related to digital logic circuits

Binary logic allows for a high-low state, true-false, +V-0, that relate to voltage levels. One level is tested for – the absence assumes the alternative.

- Within the windows of acceptable levels, interpretation is 100% correct.
- Outside these windows, and the error rate increases - hardware induced errors.
Related to digital logic circuits

High frequency noise on the bus voltage may cause an error in the read state as it bounces in and out of the 100% "window of acceptable" limits.

- Noise is generated by inductive elements within the traces as well as the IC and the capacitor.
- Multi-plane boards have greatly reduced external inductance, but have not eliminated it.
Related to digital logic circuits

Resistive elements also contribute to a delay in transmission. These elements could be in the power source to the board and contribute to a general lowering of the bus levels.
Related to digital logic circuits

"Droop" occurs when the bus cannot be held at the desired level when a multitude of devices are being switched on simultaneously. Overall capacitance needs to be increased.

Windows of acceptable levels
Next to each and every IC, a capacitor is mounted.

The capacitor acts as an energy reservoir, that can replenish the IC thirst for a quick burst of joules.
No decoupling creates delay

I need some charge!

Charge coming up!

Charge coming up!

Charge coming up!

Charge coming up!

Charge coming up!

I need some charge!

Power Supply
Decoupling capacitor should be able to pass multiple energy bursts to IC without appreciable loss of voltage.
Decoupling is a hand-me-down system

- The small capacitor next to the IC needs replenishments.
- The larger capacitor located at interspersed locations on the board, feed the smaller.
- Larger power entry capacitors located near the bus feed supply the previous group.
- The filter capacitors feed the power entry capacitors.
Filtering can have two distinctive functions that both remove unwanted signal or line variations:

- **Frequency Selective Filtering**
  - A low pass, high pass, or band pass configuration
  - Most often used application is high frequency by-pass

- **Rectified AC Smoothing**
  - Eliminates the pulsing from low to peak by alternately absorbing energy during the peaks, and releasing it during the valleys.
As frequency increases, more of the signal chooses the alternative path, less goes to the load. A variation of this circuit will allow only the higher frequencies to go to the load as the lower frequencies are channeled around it.
Voltage is pulsing with time

Capacitor charges as voltage attempts to go high, and discharges as voltage attempts to go low.

Capacitance value is high as it must stabilize this voltage and feed current to circuit during discharge.

High ripple currents!!

ESR is of critical importance (ripple voltage & heat - efficiency)

Capacitance stabilization acceptable for ±20% variations.
Capacitor Usage

- Input Filter
- Power Decoupling
- Snubber
- Coupling
- Small Signal Control
- Resonator
- Snubber
- Output Filter
SMPS – On/Charge

Switch Closed

Current Supplied

Charge Capacitor

Load Current

Supply Load Requirements
SMPS – Off/Discharge

Switch Open

Current Supplied Stopped

Discharge Capacitor

Load Current

Supply Load Requirements
SMPS Timing Diagram - Full Power

Input Current
- Switch On / Current High
- Switch Off / Current Off

Capacitor Current
- Switch Off / Discharging
- 0 Current
- Switch On / Charging

Capacitor Voltage / Load Voltage / "RIPPLE"
- Nominal DC
- Maximum Swing
- Average or DC Output
- Minimum Swing
The magnitude of the ripple is inversely proportional to the magnitude of the capacitance or the RC time constant.

If the load is kept constant and the ESR is ignored, then the amount of voltage the capacitor discharges to, is inversely proportional to the capacitance.

Higher capacitance - longer RC time constant, or the lower discharge in given time period.

Higher ripple

Lower capacitance - lower RC time constant, or the more discharge in given time period.

Lower ripple

Nominal DC
ESR Inhibits Capacitor Charge

\[ V_C = V_{L(Closed)} - V_{ESR} \]
ESR Robs Capacitor Discharge

\[ V_{L(Open)} = V_C - V_{ESR} \]

- Switch Open
- Current Stopped
- Discharge Capacitor
- ESR
- Load Current
- Supply Load Requirements

\[ V_{L(Open)} = V_C - V_{ESR} \]
The magnitude (peak-to-peak) of the ripple is proportional to the magnitude of the ESR above a critical level.

If the capacitance and load are kept constant and the ESR is increased, then the amount of voltage the capacitor charges to is a step less than the peak voltage noted during the "on cycle".

High ESR - capacitor not charged, to continue voltage drops to lower level then discharges.

Low ESR - capacitor charges to input voltage, and then discharges from that level.
at Room Temperature (~20°C)

Based on ‘measured’ values

If the capacitance and load are kept constant and the ESR step voltage adds to the overall ripple effect at room temperature, and the DC bias on the ceramic capacitor is low in relation to its rating: CR ripple slopes are equal & difference is ESR step voltage.

If this is tantalum, then this could be ceramic.

Nominal DC

Higher ripple

High ESR - capacitor not charged to continue voltage, drops to lower level then discharges.

ESR

CR

Ripple

Lower ripple

Low ESR - capacitor charges to input voltage, and then discharges from that level.
at DC Power & Temperature (~60°C)

(Application Response)

The ESR step voltage for the tantalum decreases as ESR decreases with increasing temperature. The capacitance of the ceramic decreases with increasing temperature causing the CR - ripple to increase. If the bias is increased to 33% of rated from 10% of rated, the ceramic capacitor loses and additional 40% of capacitance.

Lower ripple (Tantalum)
ESR step voltage decreases with increasing temperature, while CR ripple remains the same.

Higher ripple (MLC)
Lower ESR offers no advantage, lower capacitance because of bias and temperature causes increase in CR ripple.
For commercial tantalum chips, required series resistance appears as additional ESR.

\[ V_{L(Open)} = V_{L(Closed)} - 2(I \times ESR - 2I \times R_S) \]
The magnitude (peak-to-peak) of the ripple is proportional to the Summary ESR and Rs.

**Recommended Series**
- **Rs = 0**
  - T495, T5xx, A7xx
  - Recommended Series
  - Rs = 0

- **Rs = 0.1 ohms/volt**
  - T491/T494
  - Recommended Series
  - Rs = 0.1 ohms/volt
Magnitude of inductive pulse is proportional to magnitude of ESL, and to the magnitude of the current and proportional to the switching speed.

\[ V = L \times \frac{di}{dt} \]
If capacitance (C) decreases with frequency (shorter periods), then CR ripple has high slope at beginning and slope decays until it achieves stability in lower frequencies (longer periods).
Resonant Switchers

Slope determined by current/load

As load increases capacitor discharges, quicker, frequency increases to maintain desired ripple.