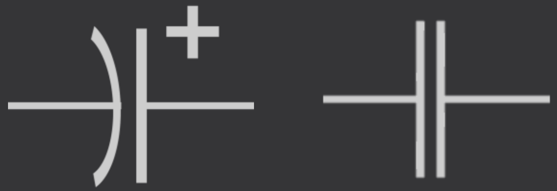
Capacitors



Purpose of this content

- This series of content is aimed at supporting engineers to gain a solid foundational knowledge on electrical and electronic components.
- Every Electrical and electronics product development starts with components. The components can be
  - **Passives :** Resistors, Inductors, Capacitors
  - **Semiconductor Discrete devices :** Various types of Diodes, Transistors, FET/MOSFETs, IGBT, Thyristors etc.,
  - **Semiconductor ICs (Actives) :** Analog, Power management, Interface ICs, MCUs, MPU, FPGAs, Sensors etc.,
- So, the first step is to get a deep knowledge on components.
  - Kowing various components available, their specifications and characteristics.
- Next step is designing circuits using components.
  - For creating and simulating the behavior of your circuits before you go for the final board design, there are few free and many paid software tools available. Getting familiar with these tools is essential optimize the development time.
  - https://www.analog.com/en/resources/design-tools-and-calculators/ltspice-simulator.html
  - https://www.ti.com/tool/PSPICE-FOR-TI

Audiences for this content

To whom this content can be useful?

- Undergraduate Engineering students from E&E, ECE, Instrumentation, Mechatronics, Computer Science or students
- Postgraduate engineering students who wants to focus on electrical, electronics products design.
- Students who are in Arts college / Diploma studying electrical, electronics subjects
- Professionals who are starting their career in embedded electronics, hardware design and system design.

Details on content creator & Request to the learner

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Because when different users visits the weblink, that will give us an idea on the number of users consuming this content and that may encourage us to continue spend time to create more such useful content and maintain this website.

Note: This content uses references to some of the great materials out there on the internet from several component manufacturers and other websites etc., We humbly recognize and thank all of those efforts which brings clarity to engineers and help making the product development great.

In case if you are an owner of such content and for some reasons you do not want the references to be a part of these slides, please feel free to write an e-mail to us to remove those references: e-mail: seekerssignpost@gmail.com

Please send us your comments, feedback, content requirement.

Why is it essential to learn in depth about Capacitors?

- **Precision in Design:** Superficial knowledge leads to suboptimal or unreliable designs. Understanding dielectric properties, frequency behavior, and parasitic effects of capacitors ensures robust circuits.
- **Innovation:** Detailed knowledge enables engineers to push boundaries, such as designing compact wearables or high-efficiency power systems, by leveraging capacitor advancements.
- **Problem-Solving:** Complex systems (e.g., mixed-signal PCBs, motor drives) require nuanced capacitor choices to address specific challenges like EMI or transient response.
- **Interdisciplinary Impact:** Capacitors appear in electrical, mechanical (vibration sensors), and biomedical (defibrillators) systems, so engineers across domains benefit from this knowledge.

Content List

- Capacitance
- Capacitor, current and voltages, energy stored,
- Waveforms in DC, AC Circuits
- Series, Parallel connection of capacitors
- Categories of capacitors
- Capacitance, ESR, Ripple current range of various capacitors
- Specification of capacitors
- Aluminum Capacitors
- Film Capacitors
- MLCC (Ceramic) capacitors, Characteristics
- Equivalent circuit of a capacitor, ESR, ESL
- Effect of ESR in switch mode power supply filter application
- Effect of ESL in IC power supply decoupling applications
- Calculation for Decoupling capacitor, DC Link Capacitor
- Capacitors in power electronics, automotive
- Ripple current rating of capacitors
- EMI filtering capacitors

Simple formulas to start with

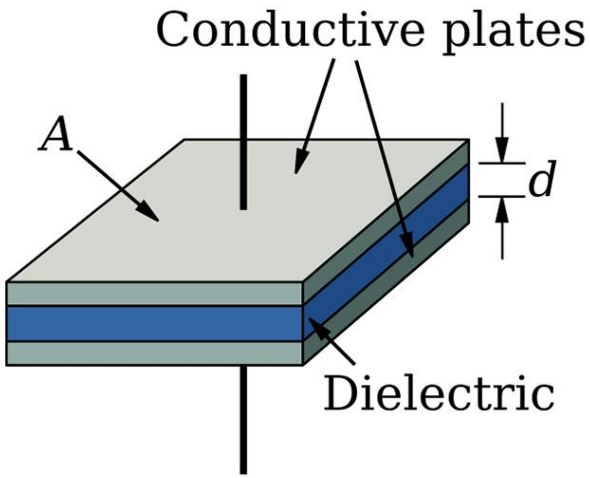
Formula Description	Resistor	Inductor	Capacitor
Defining Equation	$R = \frac{V}{I}$ (Ohm's Law)	$L = \frac{V}{\frac{di}{dt}}$	$C = \frac{Q}{V}$
Physical Property Formula	$R = \rho \frac{l}{A}$	$L = \frac{\mu N^2 A}{l}$ (solenoid)	$C = \epsilon \frac{A}{d}$
Series Connection	$R_{total} = R_1 + R_2 + R_3 + ...$	$L_{total} = L_1 + L_2 + L_3 + ...$	$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + ...$
Parallel Connection	$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ...$	$\frac{1}{L_{total}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + ...$	$C_{total} = C_1 + C_2 + C_3 + ...$
Energy Stored	Not typically stored (dissipated as heat)	$E = \frac{1}{2} L I^2$	$E = \frac{1}{2} C V^2$
AC Reactance	None (constant resistance)	$X_L = 2\pi f L$	$X_C = \frac{1}{2\pi f C}$
Power Dissipation (DC)	$P = I^2 R$ or $P = \frac{V^2}{R}$	None (no power dissipation in ideal case)	None (no power dissipation in ideal case)
Time Constant	Involved in RC and RL circuits	$\tau = \frac{L}{R}$ (in RL circuit)	$\tau = RC$ (in RC circuit)

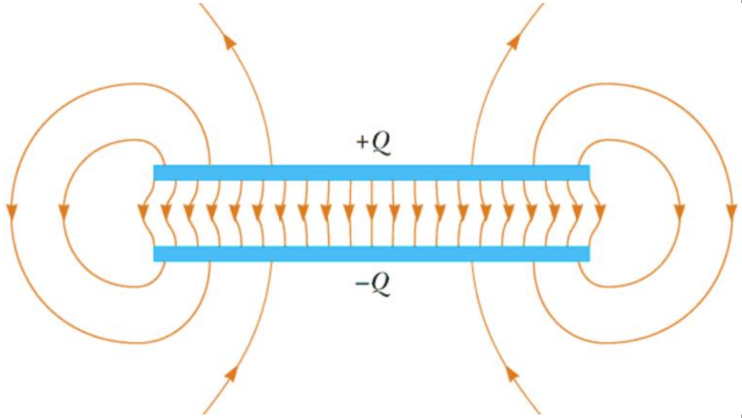
- "ρ = resistivity, μ = permeability, ϵ = permittivity"
- Units: Time constant (τ) is in seconds (s), with R in Ohms (Ω), C in Farads (F), and L in Henries (H).
- Time Constant For Capacitor: τ=RC is the time constant in an RC circuit, representing the time it takes for the capacitor to charge to ~63% of its final voltage (or discharge to ~37%).
- For Inductor: τ=L/R is the time constant in an RL circuit, indicating the time for the current to reach ~63% of its final value (or decay to ~37%).

Capacitance "C"

- Capacitance is the ability of a system to store electric charge
- Charge on a Capacitor $Q = C * V$.

  Where: Q (Charge, in Coulombs) = C (Capacitance, in Farads) x V (Voltage, in Volts)
- Capacitor with solid as dielectric $C = Q / V = \varepsilon_0 * \varepsilon_r * (A / d)$.
  - A is the area of the plates in square metres, m^2,
  - d is the distance or separation between the two plates.
  - ε_0 (epsilon) is the permittivity of free space / vacuum(8.854×10^{-12} F/m)
  - ε_r is the relative permittivity of the dielectric medium used between the two plates. Relative permittivity is a dimensionless number.
  - The farad (symbol: F) is the unit of electrical capacitance, the ability of a body to store an electrical charge, in the International System of Units (SI), equivalent to 1 coulomb per volt (C/V).





Current, voltage in a capacitor

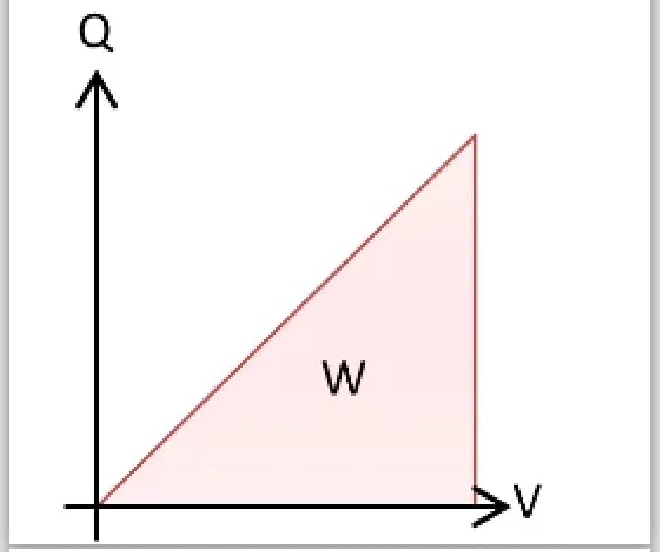
- Charge on a Capacitor $Q = C * V$.
- Voltage $V = \frac{Q}{C} = \frac{1}{C}\int_0^t idt + V_o$
- Current-Voltage (I – V) relationship. $i_{(t)} = C * dv/dt$
  - $i_{(t)}$ is the instantaneous current in capacitor
  - C is the capacitance
  - dv/dt is the instantaneous rate of voltage change in the capacitor
- Capacitive reactance

$$X_C = \frac{1}{\omega C} = \frac{1}{2 \times \pi \times f \times C}$$

- ω = 2 x π x f,
- f = frequency in Hz,
- C = capacitance in F.

Energy stored in a capacitor

- The work done in charging a capacitor appears as electric potential energy.
- Stored energy increases as the total charge, potential difference increases.
- Energy stored $E = \frac{1}{2}CV^2$
- These make capacitors useful for:
  - Camera flashes - releasing energy rapidly
  - Backup power supplies - storing charge to release when needed
  - Smoothing potential difference fluctuations - charging up then discharging

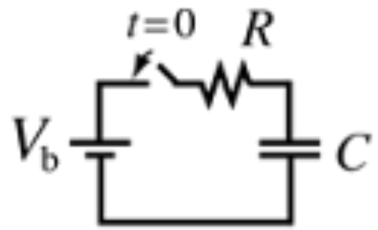


Energy stored in a capacitor:

$$W = \frac{QV}{2} = \frac{CV^2}{2} = \frac{Q^2}{2C}$$

Capacitor voltage and current waveforms-1

Waveforms for a step DC input voltage to a capacitor through a series resistor



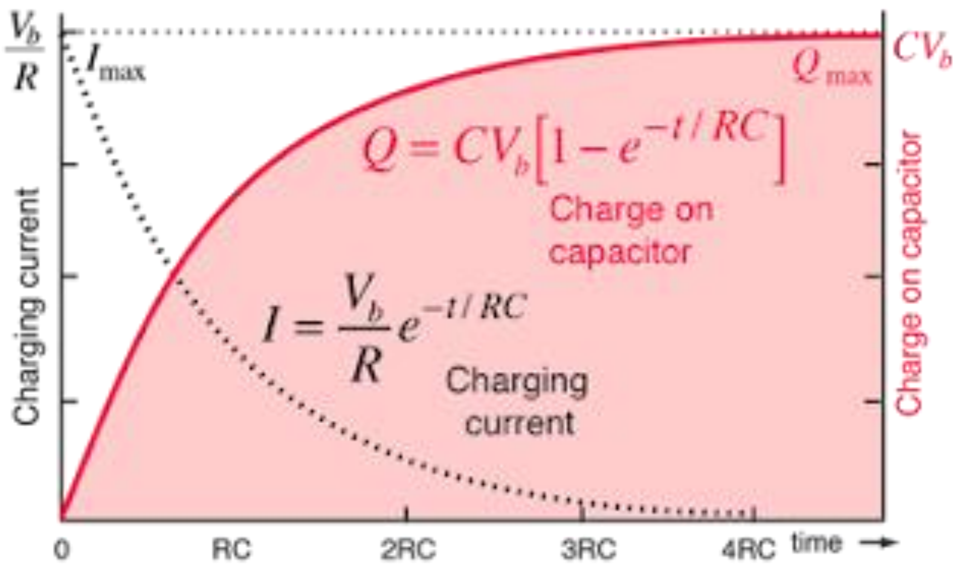
$$V_b = V_R + V_C$$

$$V_b = IR + \frac{Q}{C}$$

As charging progresses,

$$V_b = IR \Downarrow + \frac{Q}{C} \Uparrow$$

current decreases and charge increases.



At $t = 0$

$Q = 0$

$V_C = 0$

$I = \frac{V_b}{R}$

As $t \to \infty$

$Q \to CV_b$

$V_C \to V_b$

$I \to 0$

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

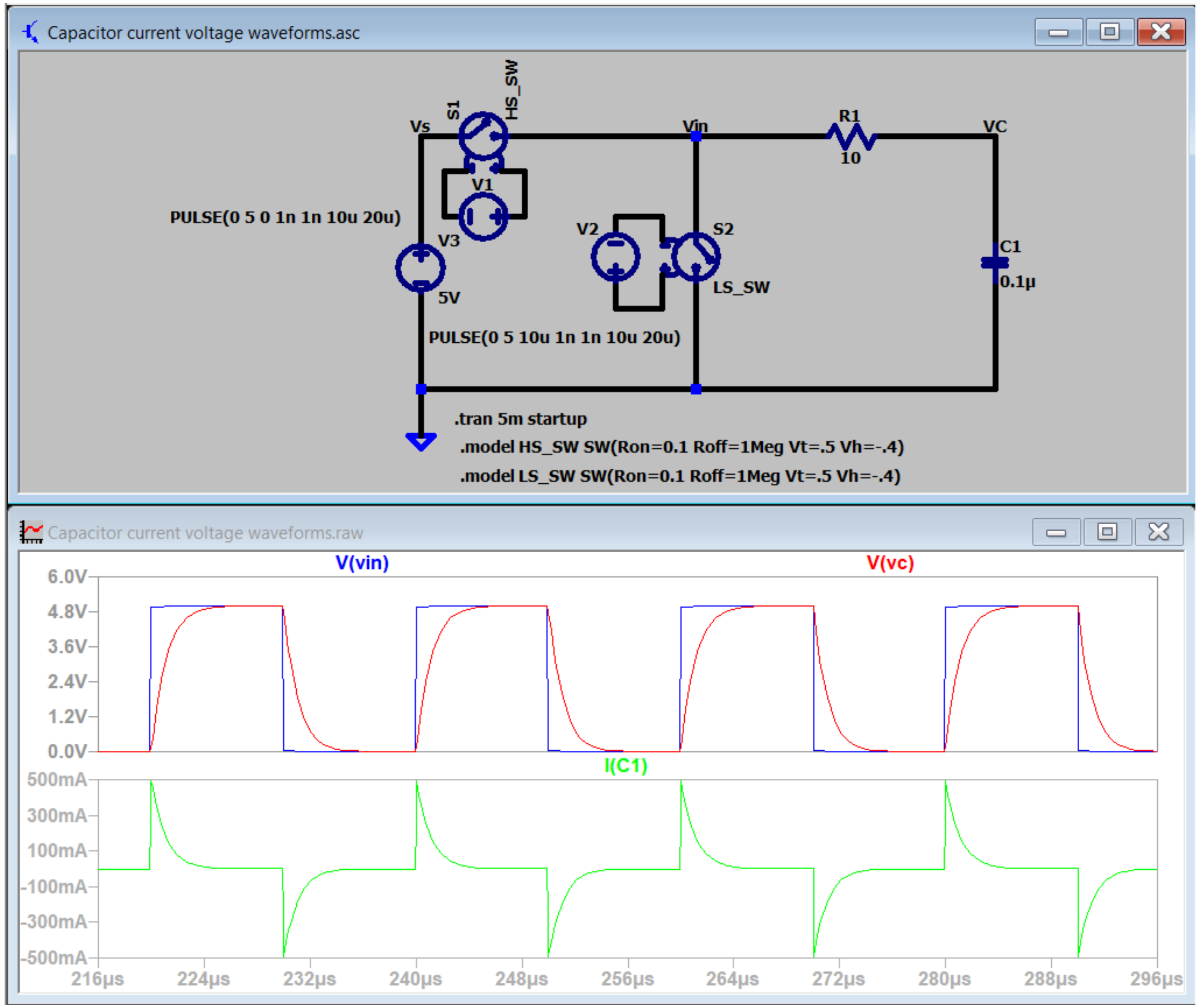
$CV = Q$;

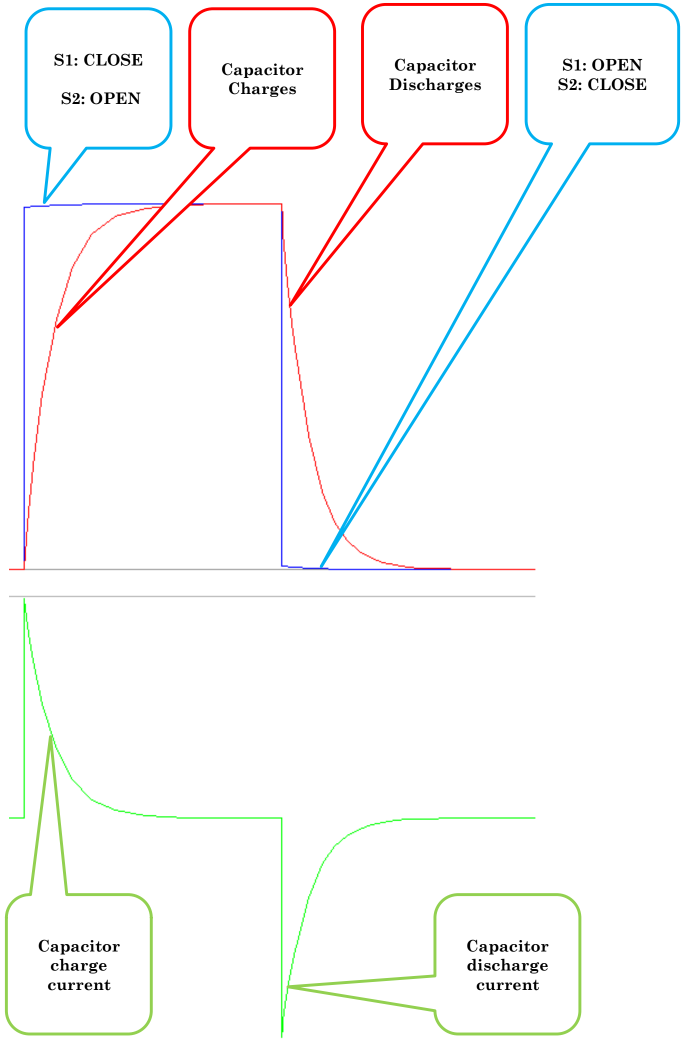
Time Constant

$\tau = R * C$

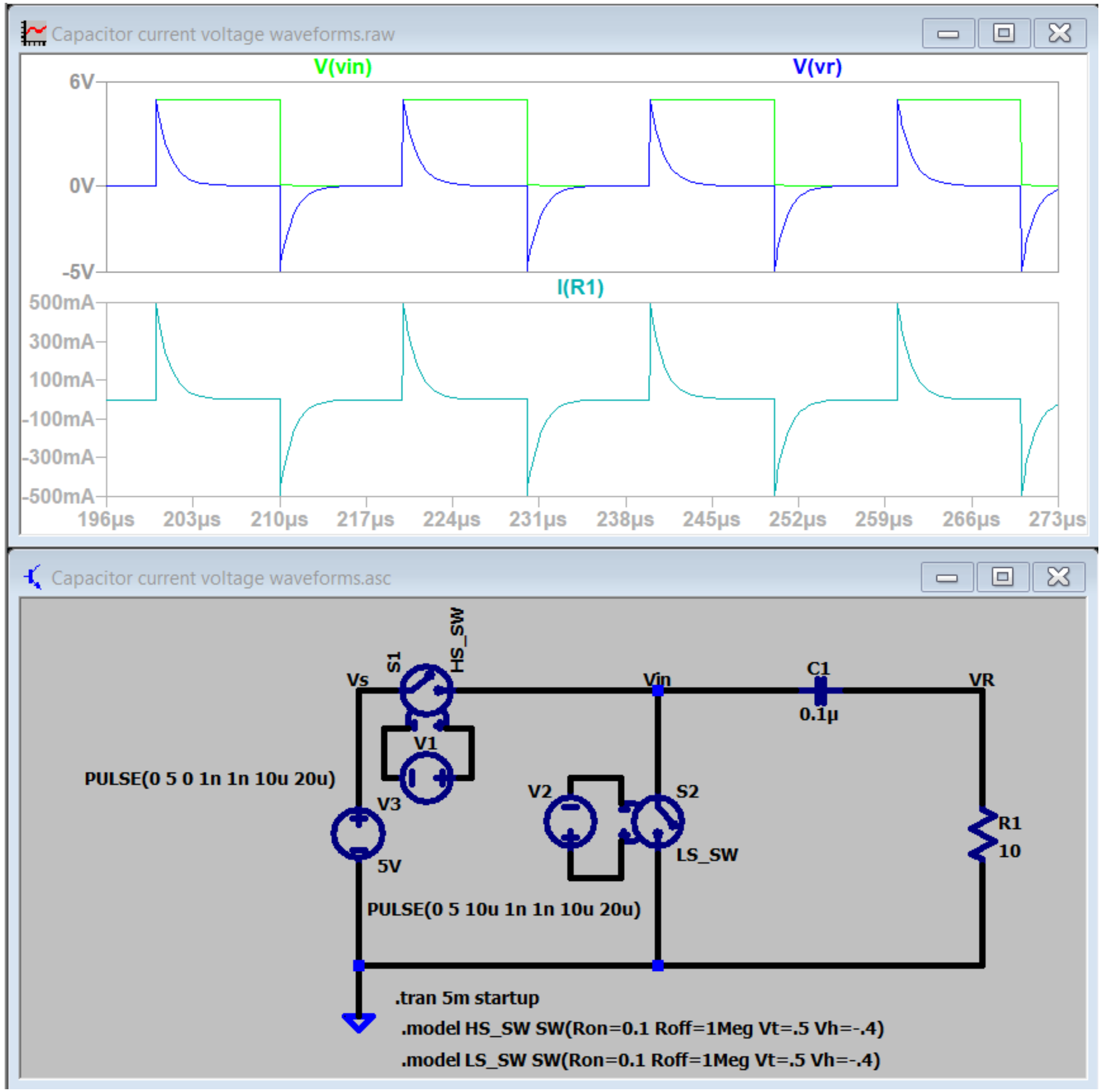
In an RC circuit, the voltage across the capacitor becomes almost equal to the input in "5 τ "

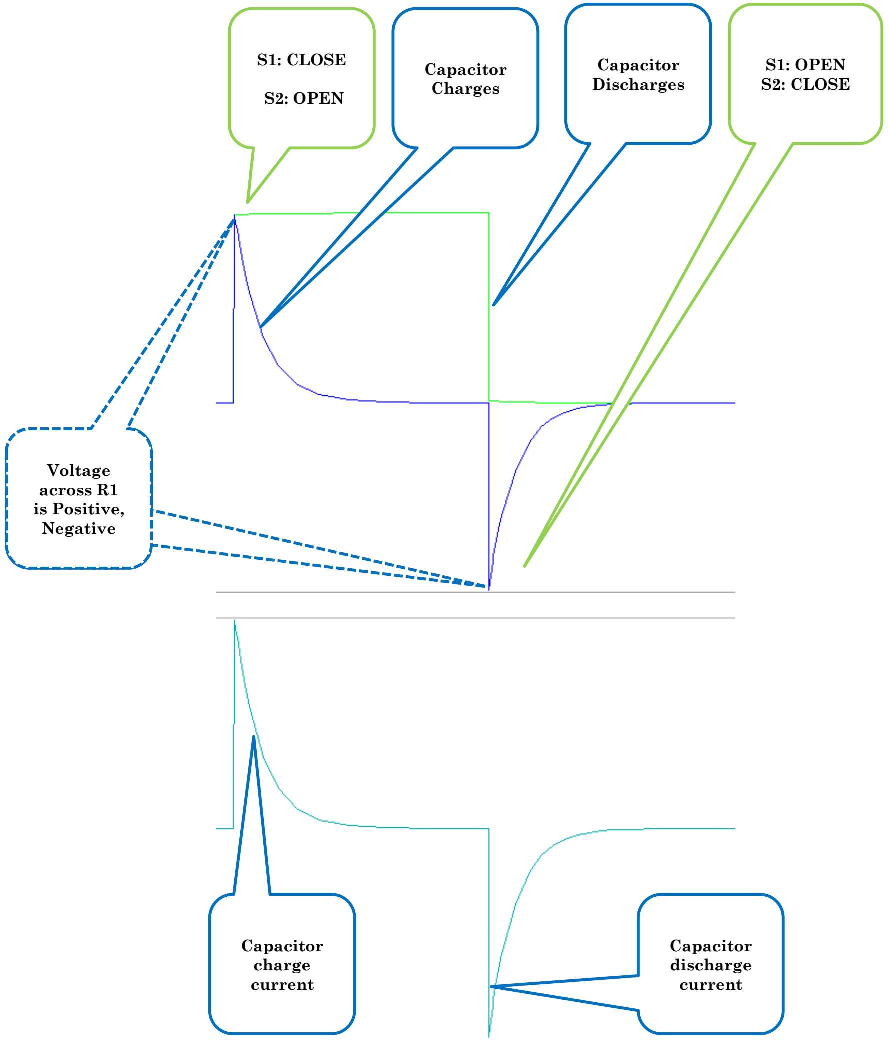
Capacitor voltage and current waveforms-2



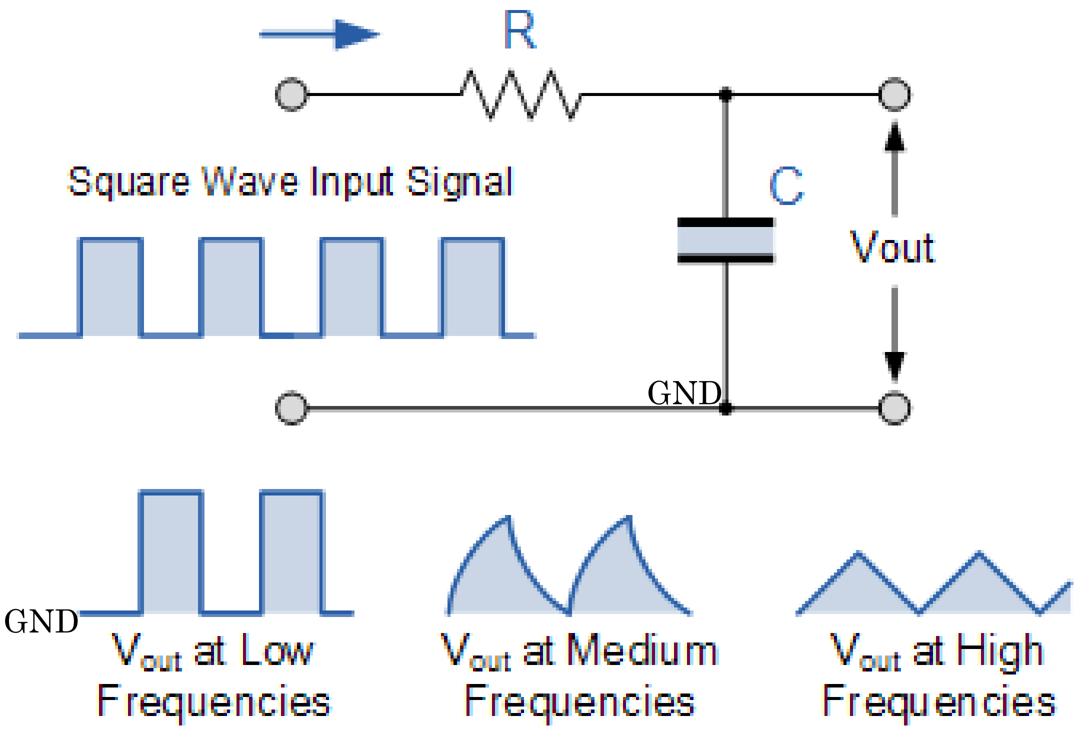


Capacitor voltage and current waveforms-3

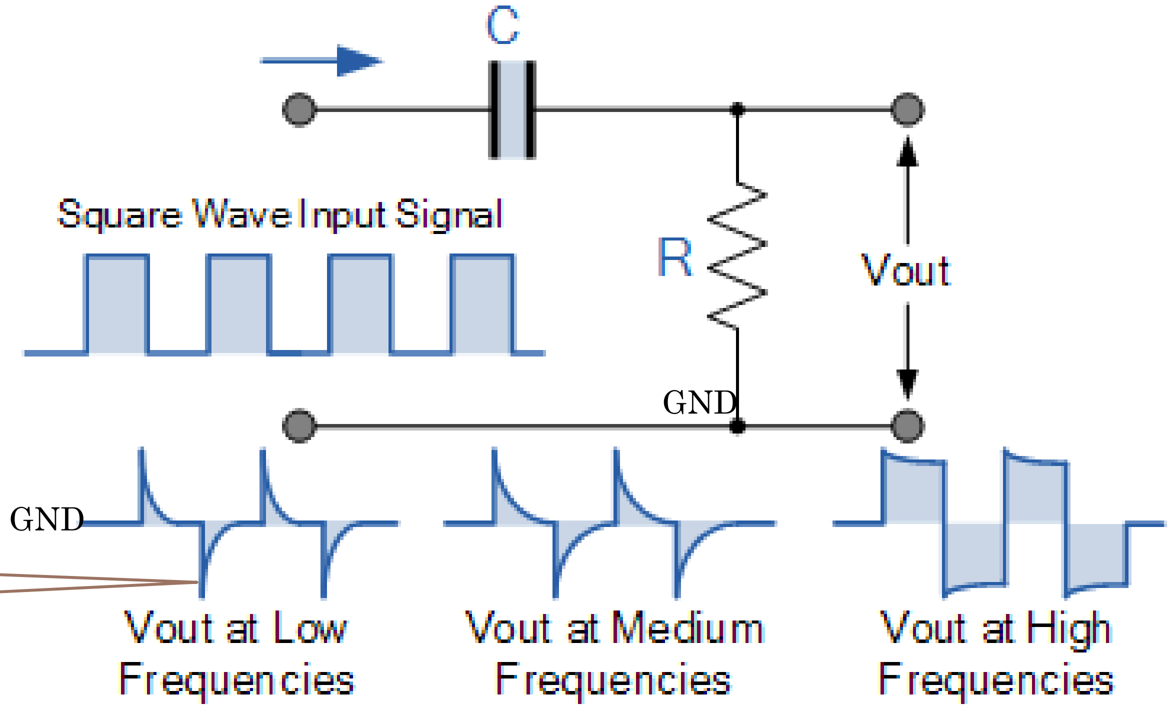




Waveforms in RC(Low pass), CR(High Pass) circuits

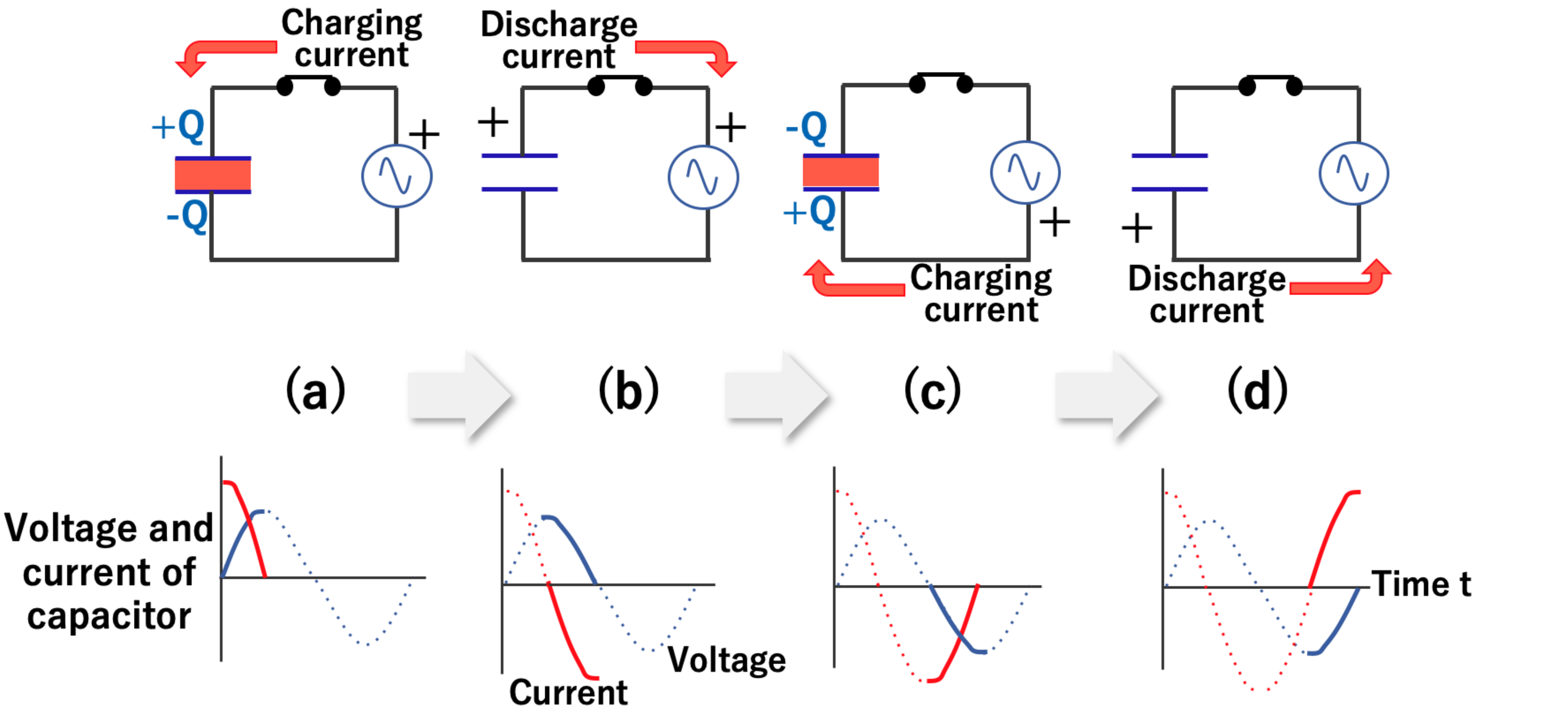


Note: Vout across R goes negative as well



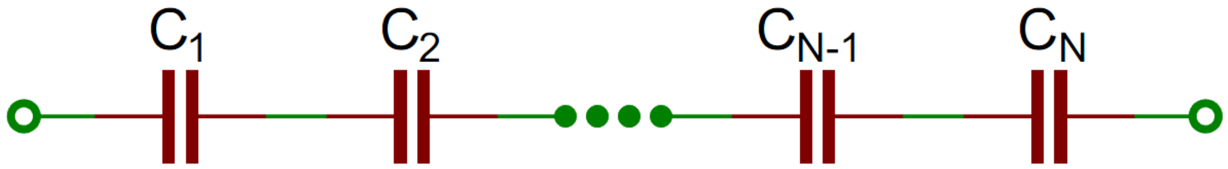
Capacitor waveforms in AC Circuit

Current waveform in a capacitor leads the applied voltage by close to 90 Degrees

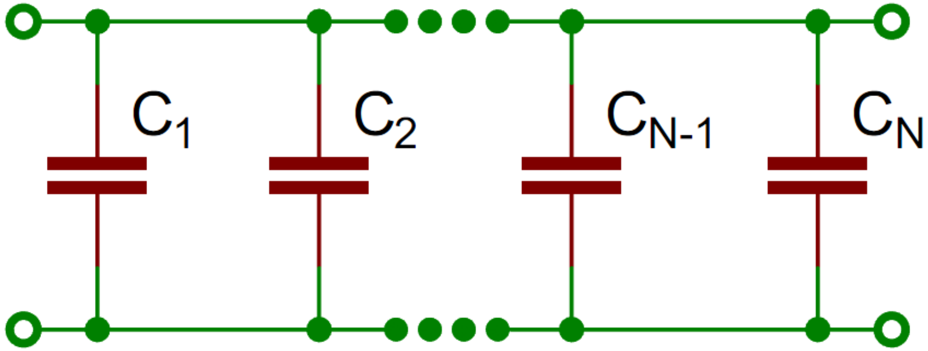


Courtesy: https://www.aictech-inc.com/en/valuable-articles/capacitor_foundation01.html

Series, Parallel connection of capacitors



$$\frac{1}{C_{Tot}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_{N-1}} + \frac{1}{C_N}$$



$$C_{Tot} = C_1 + C_2 + \ldots + C_{N-1} + C_N$$

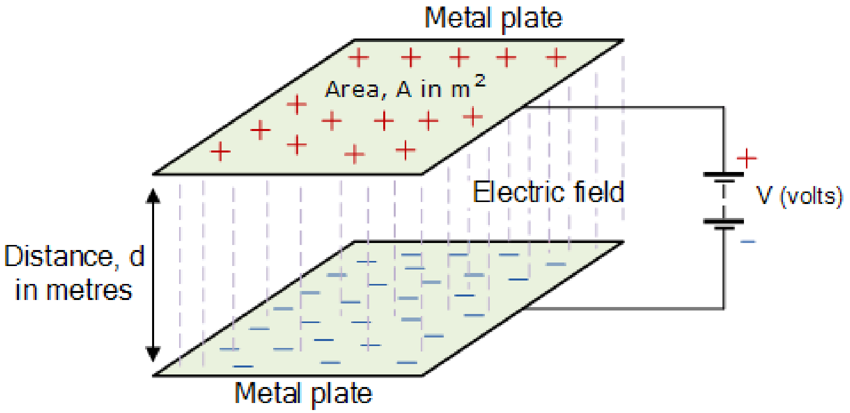
Capacitors (C)

- **Characteristic:** *Stores energy in an electric field.*
- **Function:** Store and release electrical charge, smooth voltage fluctuations, filter signals, and block DC while passing AC..
- **Behavior:**
  - Current through capacitor: I = C * dV/dt
  - Introduces **capacitive reactance**: X_C=1/2πfC

- **Key Parameter:** Capacitance (in farads, F)
- **Use Cases:**
  - AC coupling / Decoupling / Bypassing noise or EMI Filter / Power supply Filter or bulk storage capacitor / Power factor correction in AC circuits / Dropping element AC circuits / Filtering signals / Timing circuits

Parallel plate capacitor

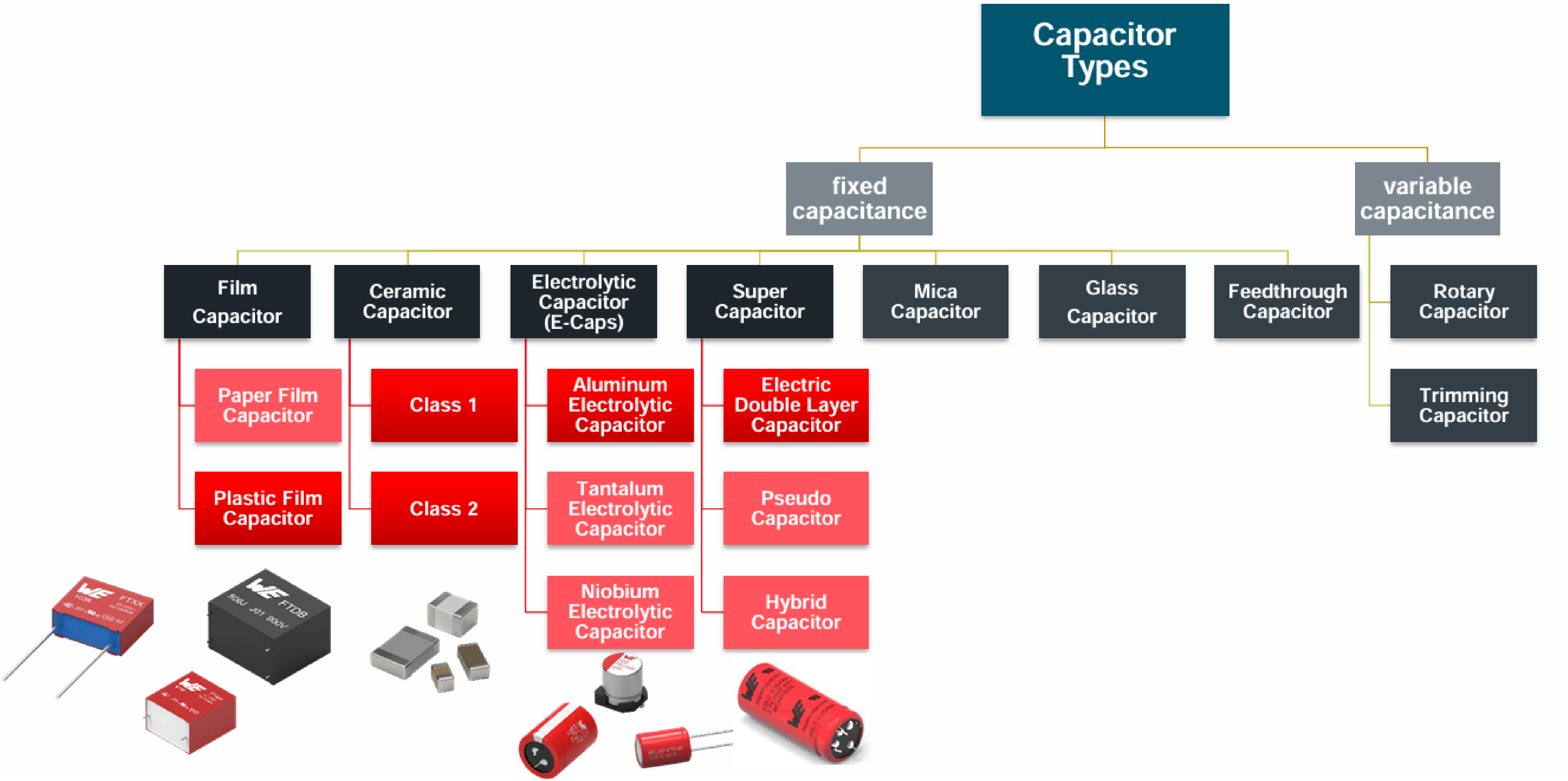
Capacitors: Two parallel conductive plates separated by an insulating material called the "dielectric".



- When a DC voltage is applied across these plates, the electrons from the plate connected to the positive terminal flow into the plate connected to the negative terminal through the DC source (but **no electrons flow through the dielectric)**.
- This movement of electrons is represented as flow of current (Current flow direction is opposite to direction of flow of electrons).
- Electric field forms across the dielectric from the positive Plate to the negative Plate and energy is stored in this field.

Different types of Capacitors

Categorization of Capacitors



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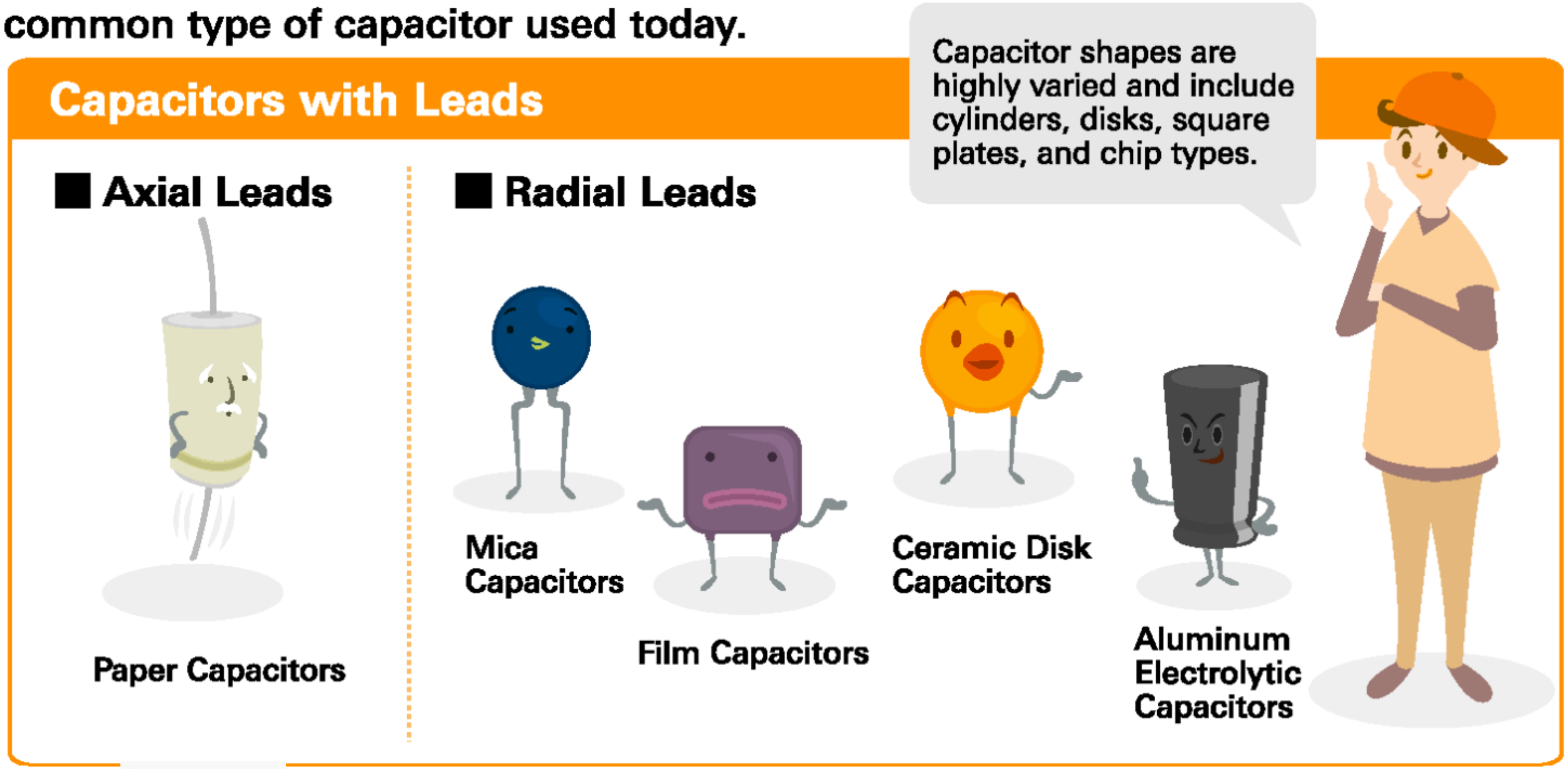
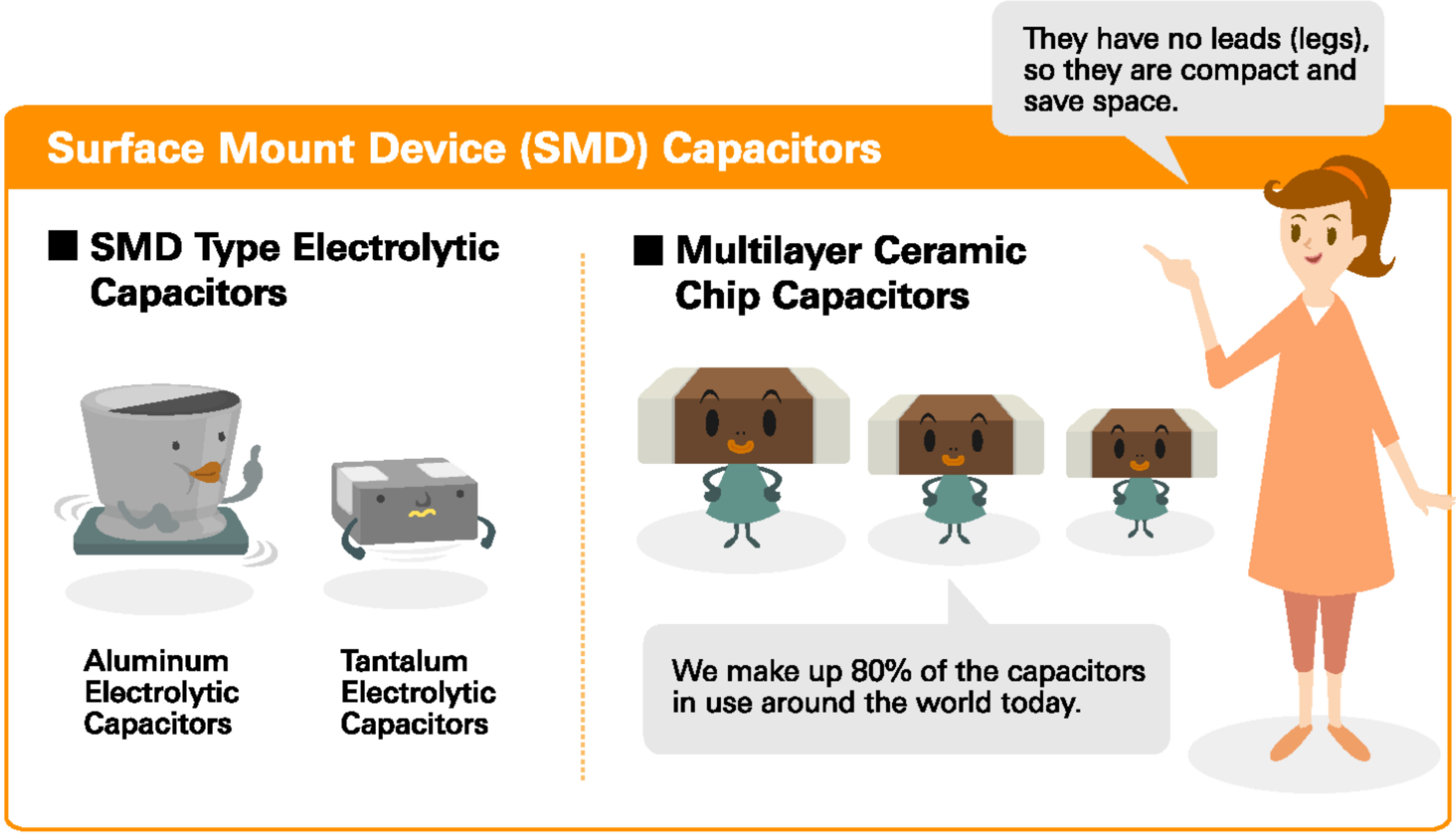
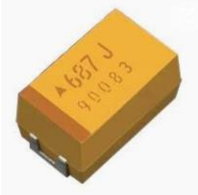
Leaded Capacitors



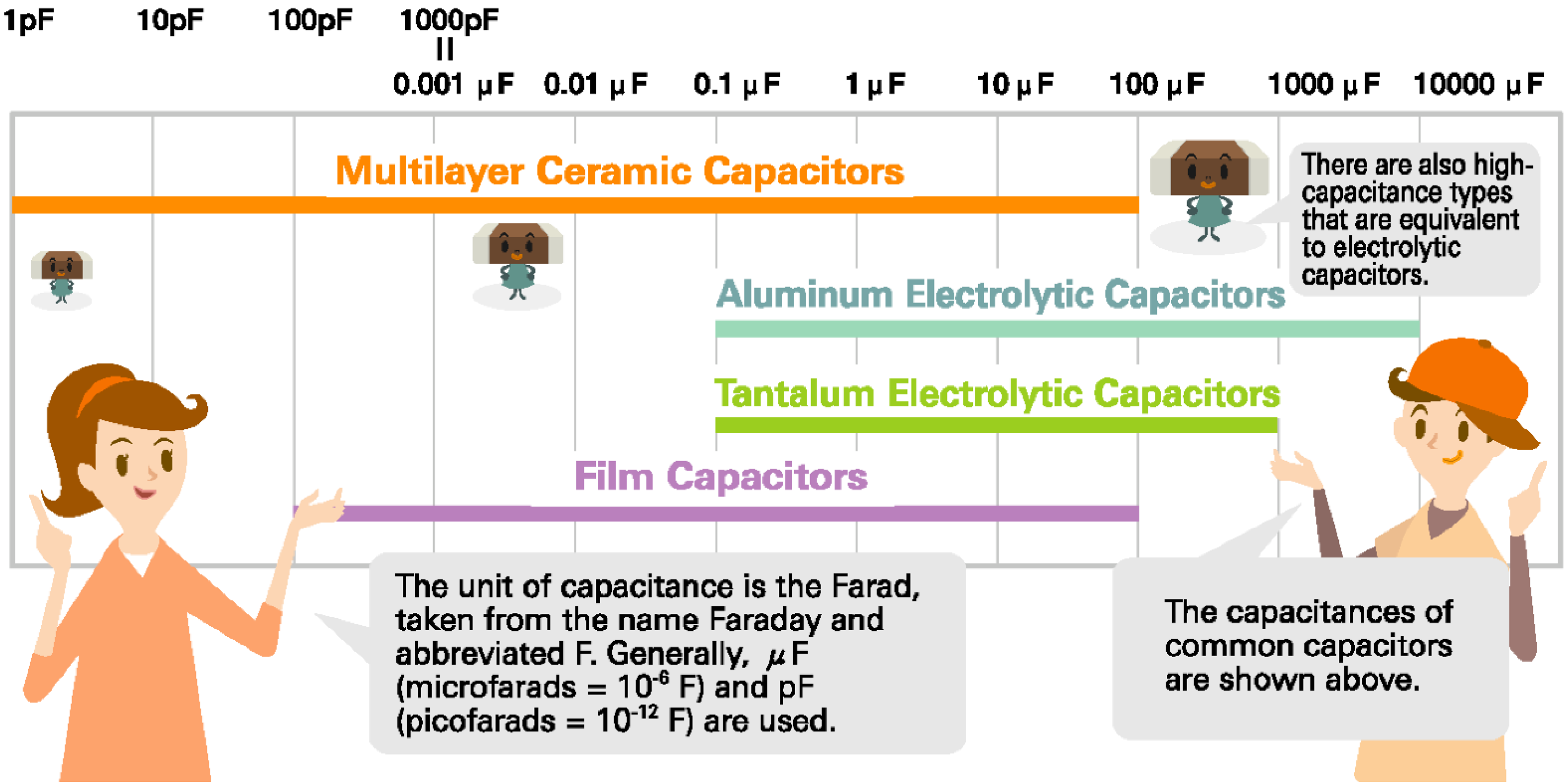
Courtesy: https://product.tdk.com/en/system/files?file=dam/doc/content/world/aaa60500.pdf

SMD Capacitors





Capacitance range for capacitors



Overview: Capacitance range, voltage, current

Technology	Max. Capacitance	Max. Voltage	Max. Current	Max. Temperature range	Application examples
Aluminum Electrolytic Capacitors	> 1F	ca. 650 V	ca. 0,05 A/µF	85 °C up to 150 °C	smoothing, storage, DC-Link
Aluminum Polymer Capacitors	> 4 mF	ca. 250 V	Ca. 0,1 A/µF	85 °C up to 150 °C	smoothing, filtering
Al. Hybrid Polymer Capacitors	> 1 mF	ca. 400 V	Ca. 0,1 A/µF	85 °C up to 150 °C	smoothing, filtering, DC Link
Film Capacitors	> 8 mF	ca. 3 kV	ca. 1 A/µF	max. 110 °C	DC Link, interference suppression, filtering
MLCC	> 100 µF	ca. 10 kV	ca. 10 A/µF	85 °C up to 200 °C	interference suppression, coupling, filtering
Supercapacitors (EDLCs)	> 350 F	ca. 3.3 V	ca. 0,21 A/F	65° up to 85 °C	UPS, storage

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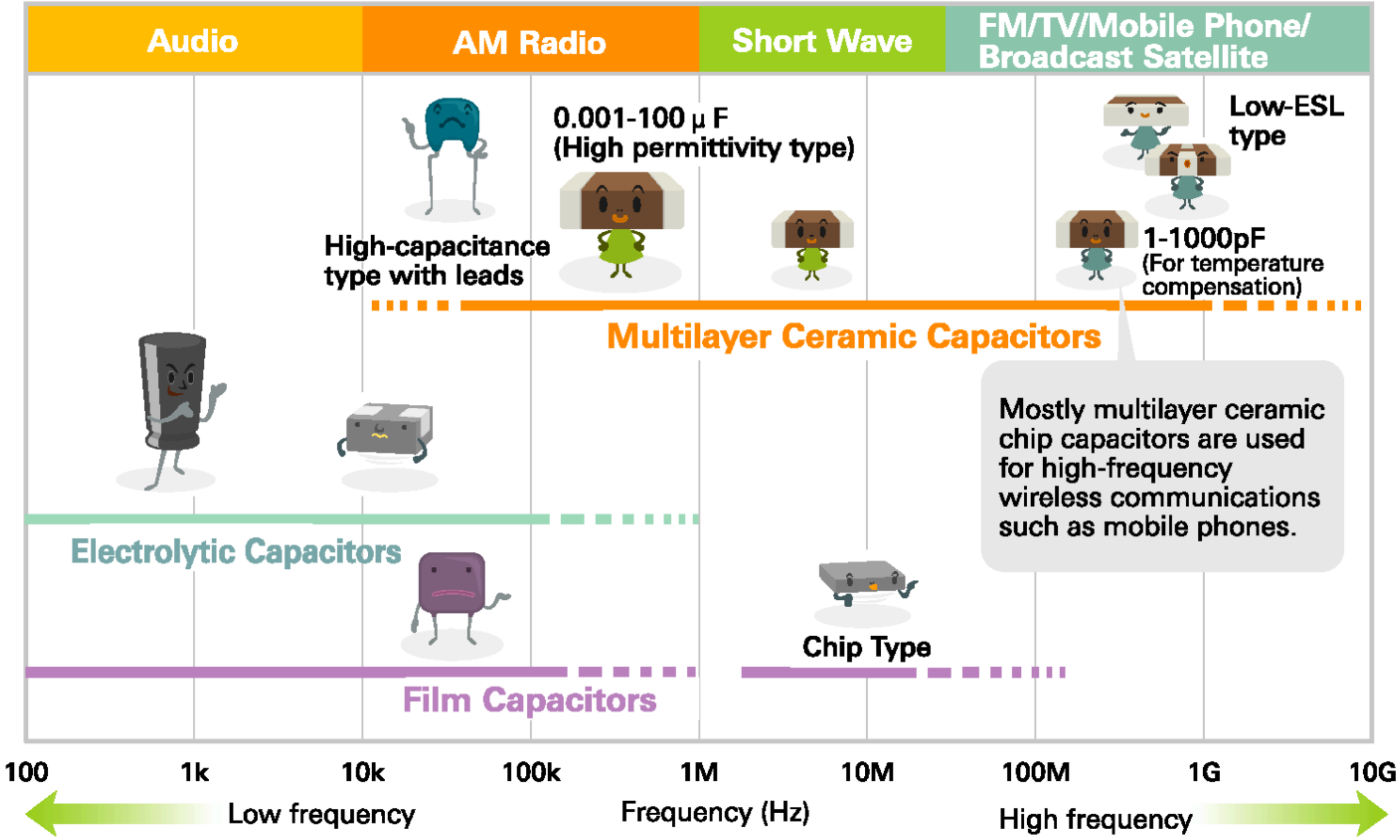
Capacitor Types, Frequency of usage



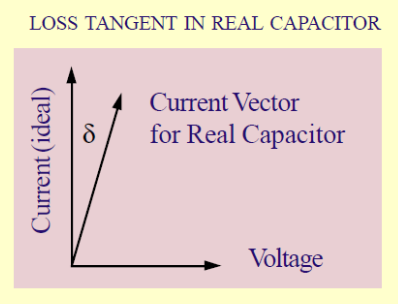
Capacitor Specifications - 1

- **Rated Capacitance (C_N):** Capacitance value rated at 20 °C / 53 Hz.
- **Tolerance on Capacitance (± .. %):** Capacitance range within which the actual capacitance may differ from rated capacitance C_N.
- **Rated DC Voltage (U_{NDC}):** Maximum operating peak voltage of either polarity but of a non-reversing type waveform, for which the capacitors have been designed, for continuous operation.
- **Ripple Voltage (U_r):** Peak to peak alternating component of the unidirectional voltage.
- **Series Resistance (R_S):** Effective ohmic resistance of the conductors of a capacitor under specified operating conditions.
- **Thermal Resistance (R_{th}):** Thermal resistance indicates by how many degrees the capacitor temperature at the hotspot rises in relation to the power losses.
- **Maximum Current ($I_{max.}$):** Maximum root mean square current for continuous operation.
- **Maximum Peak Current ($\hat{I}$):** Maximum peak current that can occur during continuous operation.

Capacitor Specifications - 2

- **Maximum Surge Current ($\hat{I}_S$):** Peak non-repetitive current induced by switching or any other disturbance of the system which is allowed for a limited number of times, for a duration shorter than the basic period.
- **Dielectric Loss Factor (tan d) :**Constant dissipation factor of the dielectric material for all capacitors in their rated frequency.
- **Inductance (L_S):** Represents the sum of all inductive elements which are for mechanical construction reasons contained in any capacitor.
- **Lowest operating temperature (Θ_{min}) :** Lowest temperature at which the capacitor may be energized.
- **Maximum operating temperature (Θ_{max}):** Highest temperature of the case at which the **capacitor may be operated.**
- **Reliability:** The operating reliability of the capacitor is determined by the number of failures, within an adequately large batch, expected to occur after a specified time (life expectancy). DIN 40040 has replaced the previous term “operating reliability” by the new term “reference reliability.”

Dissipation Factor (DF), Q, Xc, ESR



- The dissipation factor of a capacitor, often represented as "tan δ," measures the energy lost as heat within a capacitor when subjected to an alternating current (AC).
- It quantifies the capacitor's inefficiency in storing energy and is typically measured using an impedance bridge, like the Schering bridge.
- DF is a material property, and it is found that lower DF is associated with materials of lower dielectric constant K..

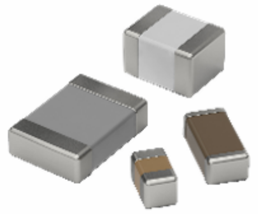
- $DF = \dfrac{\textit{Energy dissipated as heat}}{\textit{Energy stored in a cycle}}$
- A lower dissipation factor indicates a more efficient capacitor
- Q Factor of a Capacitor Q = 1 / DF
- Capacitive Reactance Xc = 1 / 2πfC
- Equivalent Series resistance (ESR) of a capacitor Rs = DF * Xc
- Power loss in capacitor = I^2 * Rs

Courtesy: https://blog.knowlescapacitors.com/blog/capacitor-fundamentals-part-14-useful-formulas-and-calculations-for-capacitors

Major capacitor technologies

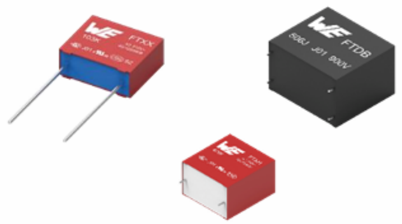
MLCC

- Smallest sizes
- High Voltage available
- Class 1 Ceramic very stable over Temperature, Voltage and Time
- Class 2 Ceramic big capacitance but mind the Capacitance losses
- Safety Capacitors available
- Limit possible cracking with soft termination



Film Capacitor

- Suitable for high Voltage
- Self-healing properties
- Safety Capacitors available
- Sensitive to humidity & temperature



Supercapacitor

- Very high Capacitance
- Strongly adviced Balancing if connected in series

Aluminum Capacitor

- Aluminum Electrolyte
  - Cost efficient
  - Big variety in size
- Aluminum Polymer
  - Suited for longevity applications
  - Low ESR values
  - Not suited for:
    - Battery powered applications
    - High vibration applications
- Aluminum Hybrid Polymer
  - Combines the advantages of both technologies
  - Suited for longevity applications
  - Suited for high temp applications

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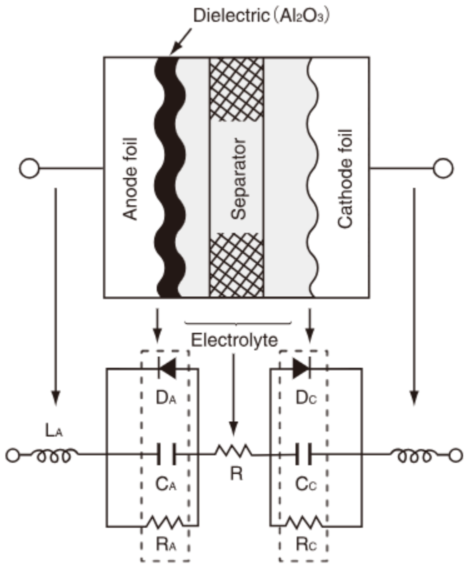
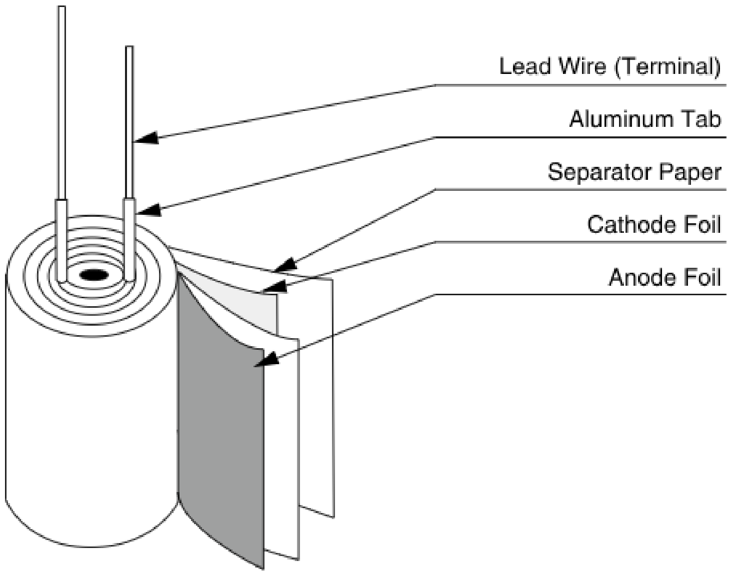
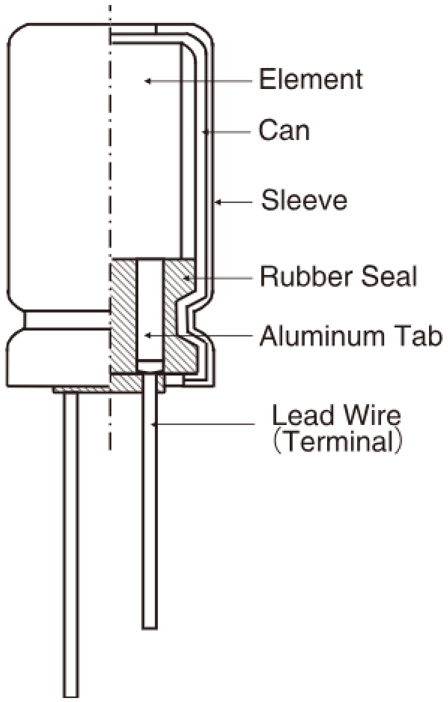
Aluminum Electrolytic Capacitors

An aluminum electrolytic capacitor comprises:

Anode…	Aluminum foil
Dielectric…	Electrochemically formed oxide layer (Al2O3) on the anode
Cathode…	A true cathode is electrolytic solution (electrolyte).



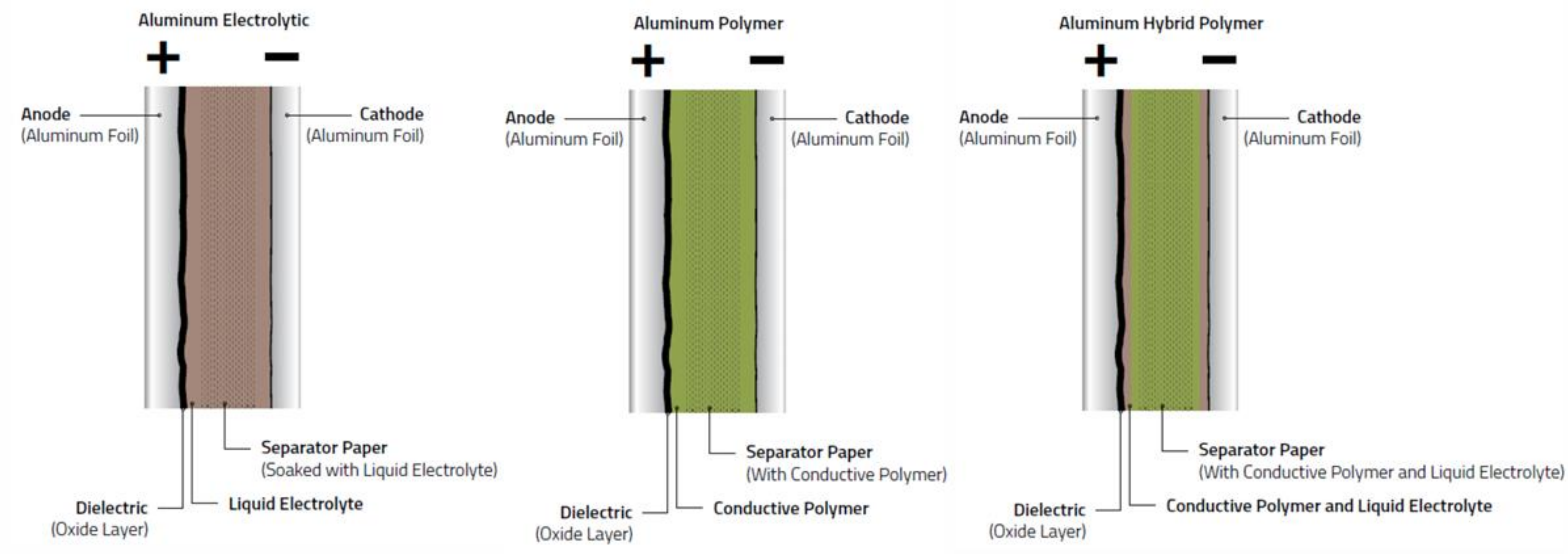




C_A、C_C	: Capacitance due to anode and cathodes foils
D_A、D_C	: Diode effects due to oxide layer on anode and cathode foils
L_A、L_C	: Inductance due to anode and cathode terminals
R	: Resistance of electrolyte and separator
R_A、R_C	: Internal resistance of oxide layer on anode and cathode foils

Courtesy: Structure of Aluminum Electrolytic Capacitor | Nippon Chemi-Con Corporation

Different Aluminum Capacitor technologies



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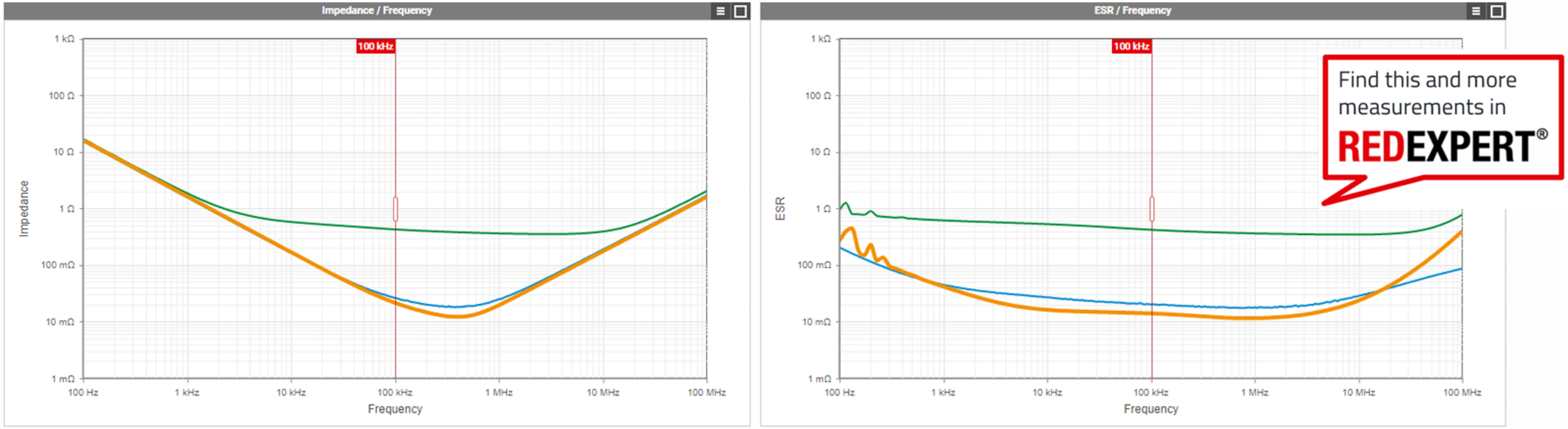
Comparison of Aluminum Capacitor technologies

	Technology	Capacitance [µF]	Voltage [VDC]	Size [mm]	ESR [mOhm, typ]	RC [mA]	LC [µA]	Temperature range	Endurance [@105°C]	Expected Lifetime [h, @65°C]
● (green)	Electrolytic	100	16	6.3x6.6	420	255	16 +	-55 to 105	2000	3.65 years max
● (blue)	Hybrid	100	16	6.3x6.6	20.1 +	1300 +	16 +	-55 to 105	10000 +	13 years max +
● (orange)	Polymer	100	16	6.3x6.6	14 + +	2690 + +	400	-55 to 105	2000	13 years max +



Polymer and Hybrid capacitors offer lower ESR, hence less heat (longer life) and higher ripple current perfect for switching applications.

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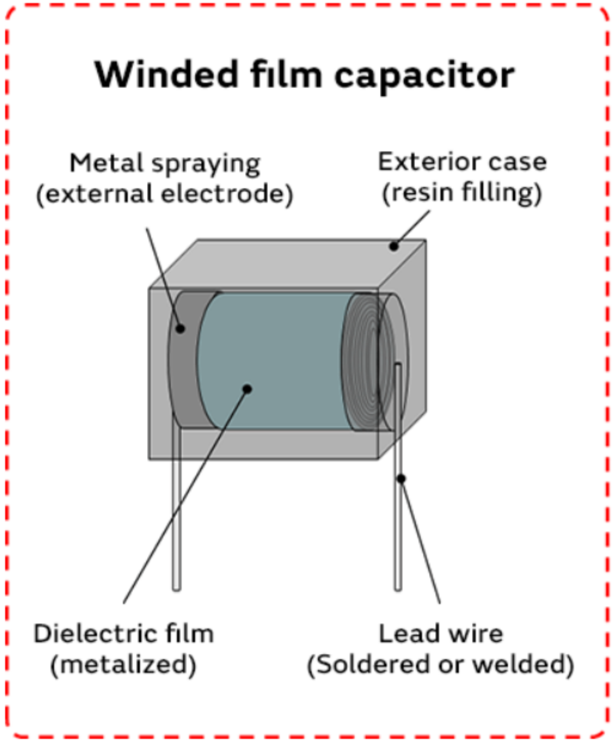
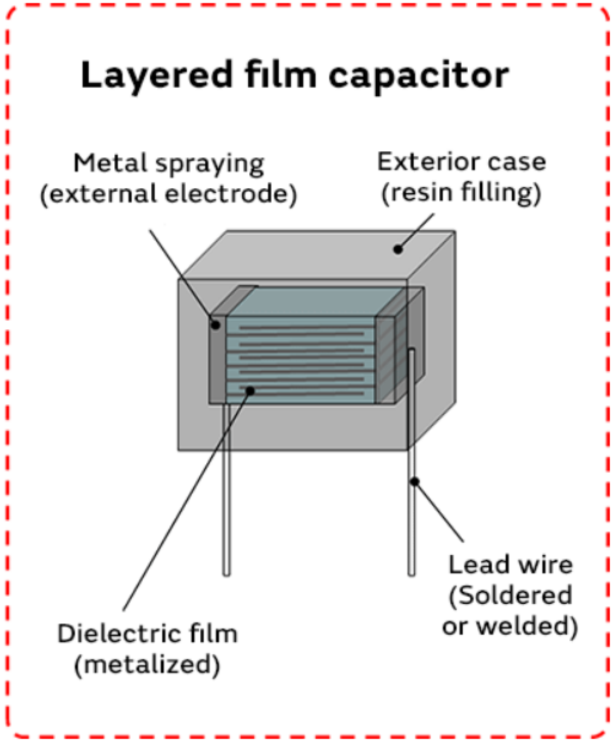
Film Capacitors

A film capacitor uses polymer film as the dielectric (Various polymer materials are used). The main types of film capacitor structures are winded and layered. Winded film capacitors contain a polymer film that is wound and pressed and inserted into a case. Layered film capacitors contain multiple layers of polymer film inserted into a case.





Courtesy: [What are film capacitors? | Film Capacitor Fundamentals | Murata Manufacturing Co., Ltd.]

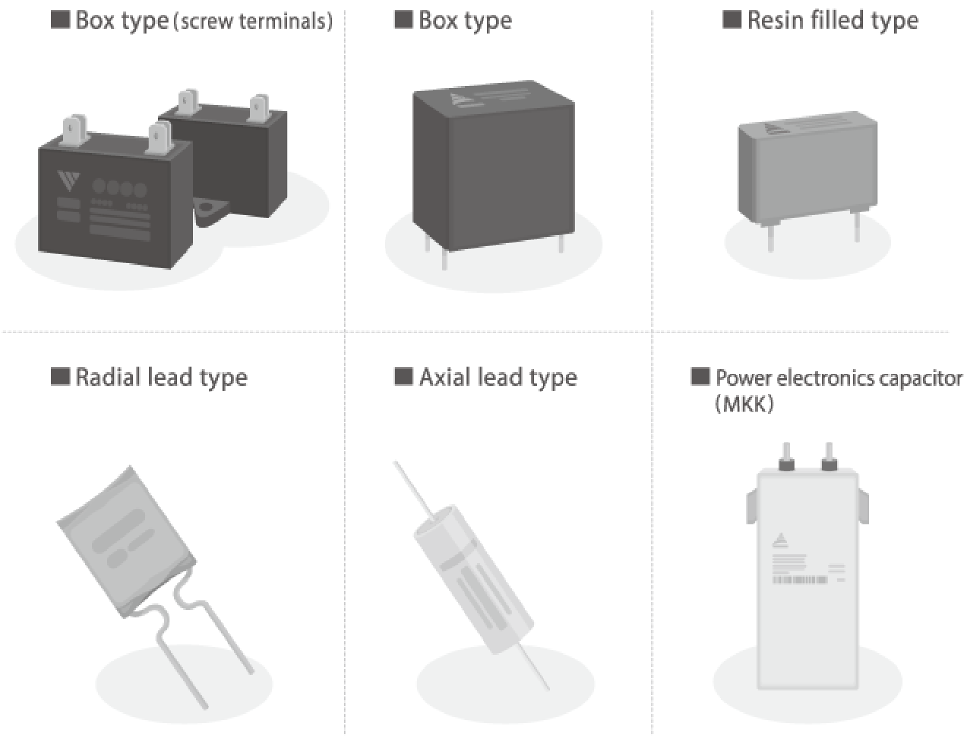
Electrolytic Vs Film Capacitors

- Aluminum electrolytic capacitors have a higher capacitance per unit volume, lower in cost. It uses the electrolyte that serves as both a conductor and a component of the cathode. This is a polarized capacitor available in 1000's of uF.
- Not suitable for high-frequency applications such as EMI filters because ESR is high and ESR increases very significantly (~100x times) at -40°C

- Metallized film capacitors use wound polystyrene / polypropylene / Teflon film along with metallized electrode made of aluminum or other material. Available in pF to few 100uF
- They are non-polarized and can be used in AC circuits. They have a longer life span, higher reliability, and slower aging than other capacitors, and their low ESR and ESL values and very low loss coefficient are also significant features.
- They can withstand kilovolt-class voltages and can also supply very high surge current pulses.

Courtesy: https://www.aictech-inc.com/en/valuable-articles/capacitor_appllication01a.html

Film Capacitors : Applications

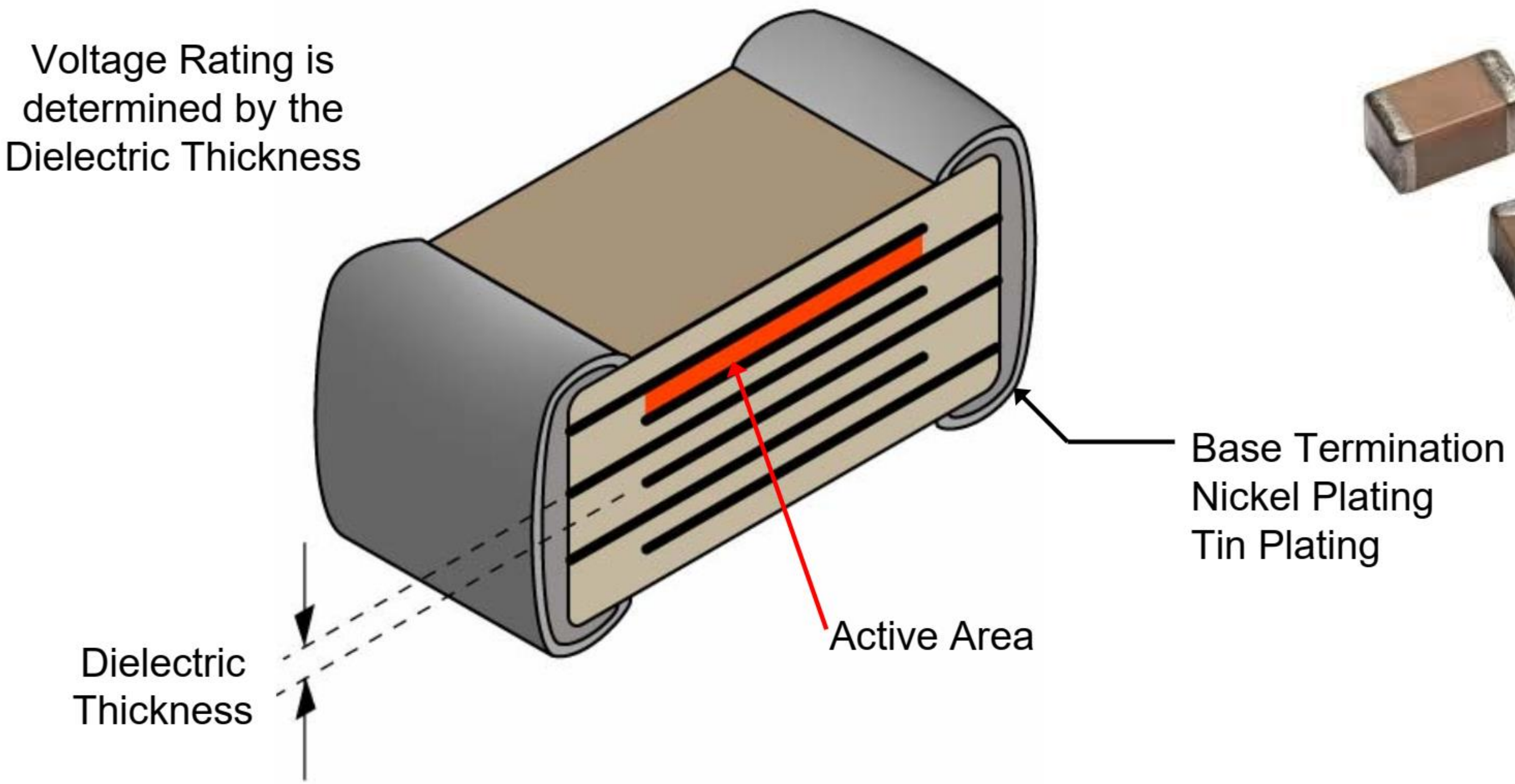


Field	Major applications
General (industrial and consumer use)	Smoothing, charge storage, DC linking, coupling, filter circuits, resonance circuits, snubber circuits, automotive use, etc.
EMI suppression	Across the line (X) capacitors for power supply EMC filtering, line bypass (Y) capacitors, etc.
Capacitive power supplies	Capacitors for smart meters connected in series with power network, and other applications requiring high reliability, stability, and durability
AC motor run	Start and operation capacitors for induction motors in industrial equipment, home appliances, etc.
Power electronics (Power capacitors)	Power factor improvement, solar powergeneration, wind power generation, UPS (Uninterruptible Power Supply), and many other applications

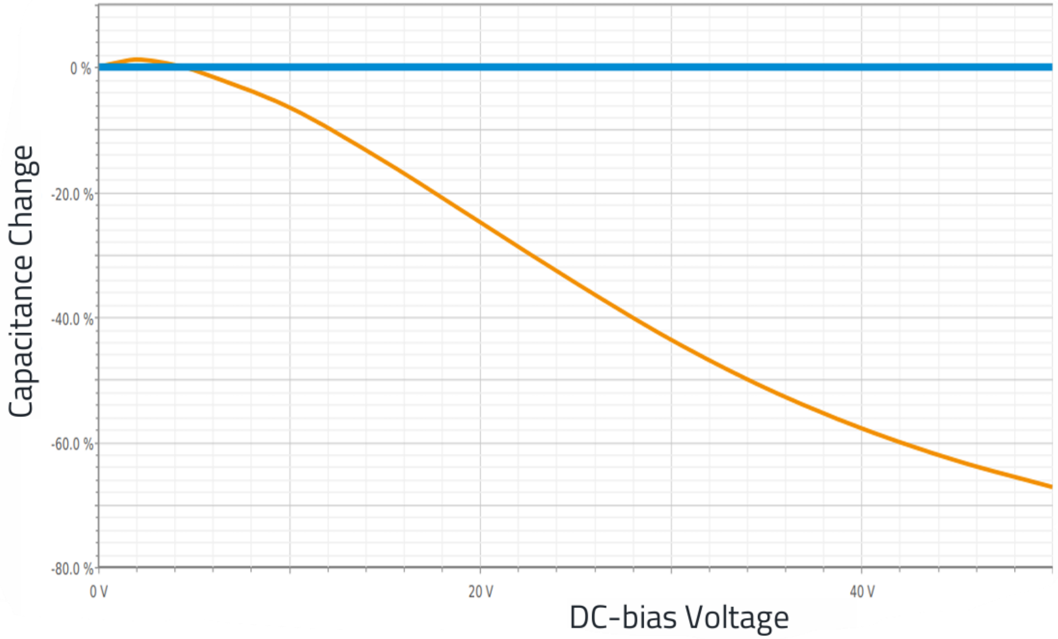
Construction of MLCC Capacitors

Used in switching power supplies as part of LC filter due to low ESR, ESL

$$\text{Capacitance} = \frac{\#\ \text{Layers} \times \text{Dielectric Constant} \times \text{Active Area}}{\text{Dielectric Thickness}}$$



Class 1 and Class 2 Dielectric MLCCs



Class 1 ceramic

- **Class 1 Ceramic** – (e.g. NP0 / C0G)
  - Relative small Permitivity ε_r >> small capcitance values possible
  - linear temperature dependency
  - Next to no aging
  - Very small voltage dependency
  - Suitable for high frequency applications

Class 2 ceramic

- **Class 2 Ceramic** – (e.g. X7R, X5R, Y5V, ...)
  - Relative high Permitivity ε_r → High capacitance values available
  - Nonlineare temperature dependency
  - Aging
  - High Voltage depency in many cases

- Class 1 Dielectric based MLCC doesn't have change in capacitance due to DC Bias voltage. However, as their size for given capacitance value is higher, they are practical only for low value capacitance (pf range).

- Class 2 dielectric cap's capacitance value reduces very significantly over DC bus voltage

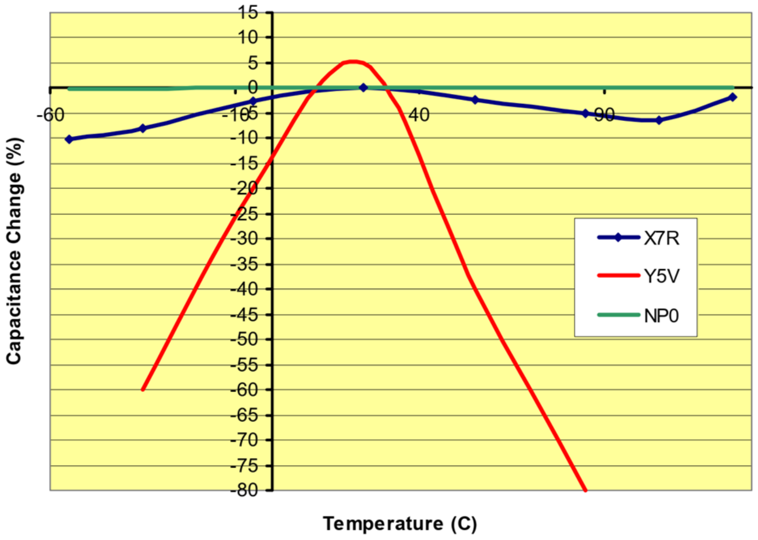
MLCC-Class 1, 2 Dielectric: Change in C Vs Temp

- Class 1 ceramic materials (e.g., NPO, COG) have very low temperature coefficients, meaning that their capacitance varies very little over temperature. They also have low dielectric constants, meaning that capacitors built with class 1 materials have very small capacitance per volume. NPO and COG are very common class 1 temperature coefficients and have a temperate coefficient of 0 and tolerance of +/-30 ppm.

- Class 2 (X,Y,Z) ceramic materials are less stable over temperature, but have a higher dielectric constant, which means that capacitors with more capacitance are available in the same volume. X7R is a very common class 2 temperature coefficient, and X7R capacitors typically have tolerance of 5%, 10%, and 20%.

- Table helps decode temperature coefficients for class 2 MLCCs

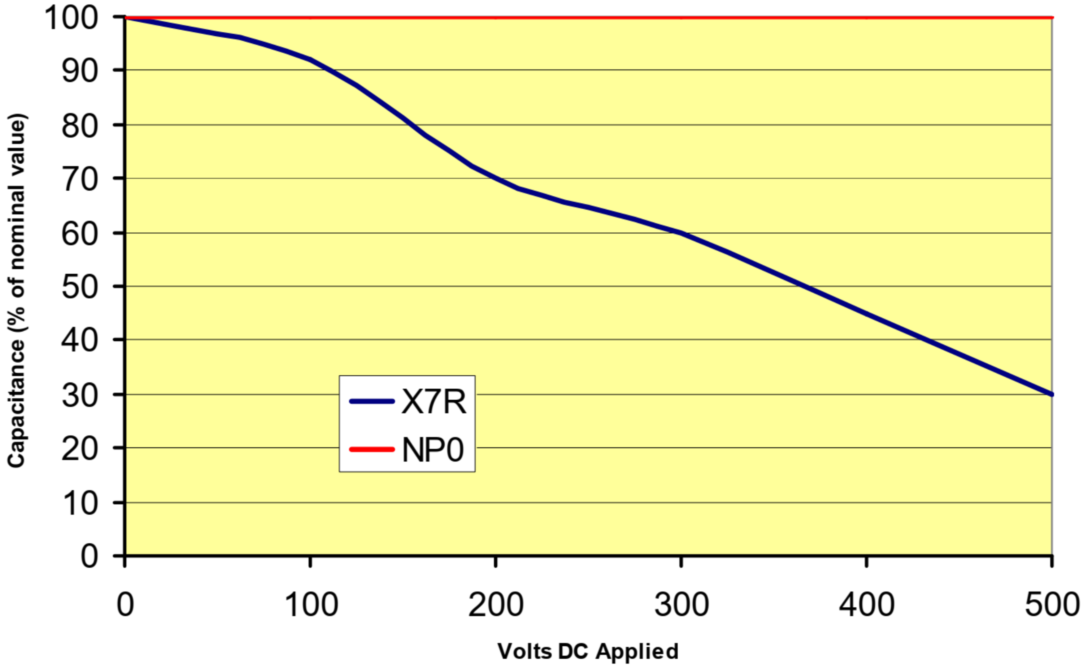
Letter code low temperature	Number code upper temperature	Letter code change of temperature over the temperature range
X = -55°C (-67°F)	4 = +65°C (+149°F)	P = ±10%
Y = -30°C (-22°F)	5 = +85°C (+185°F)	R = ±15%
Z = +10°C (+50°F)	6 = +105°C (+221°F)	S = ±22%
	7 = +125°C (+257°F)	T = +22/-33%
	8 = +150°C (+302°F)	U = +22/-56%
	9 = +200°C (+392°F)	V = +22/-82%



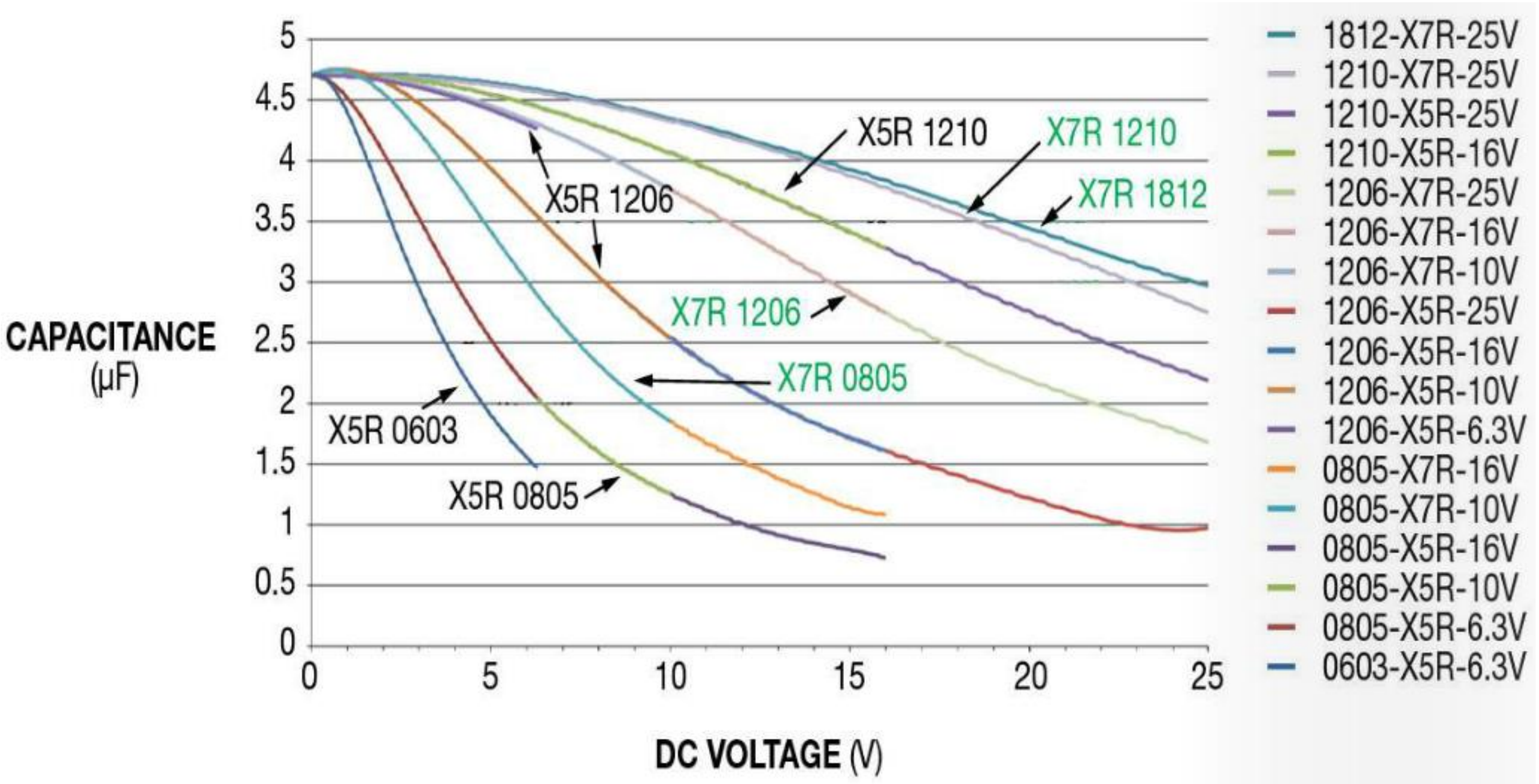
Change in Capacitance Vs Applied DC voltage

- This is a property of Class 2 ceramic materials and applies to all manufacturers.
- The graph shows typical voltage coefficient curves for 500VDC rated X7R and NP0 capacitors.
- Note that the capacitance of the NP0 remains stable with applied voltage, while the X7R material can have a capacitance loss of 80% at rated voltage
- Also electrolytic, polymer, film capacitor's capacitance doesn't change with respect to applied DC bias voltage.

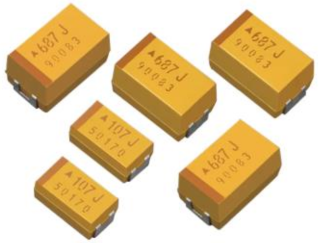
Capacitance value with respect to applied voltage (DC Bias Characteristic) for MLCC Capacitor

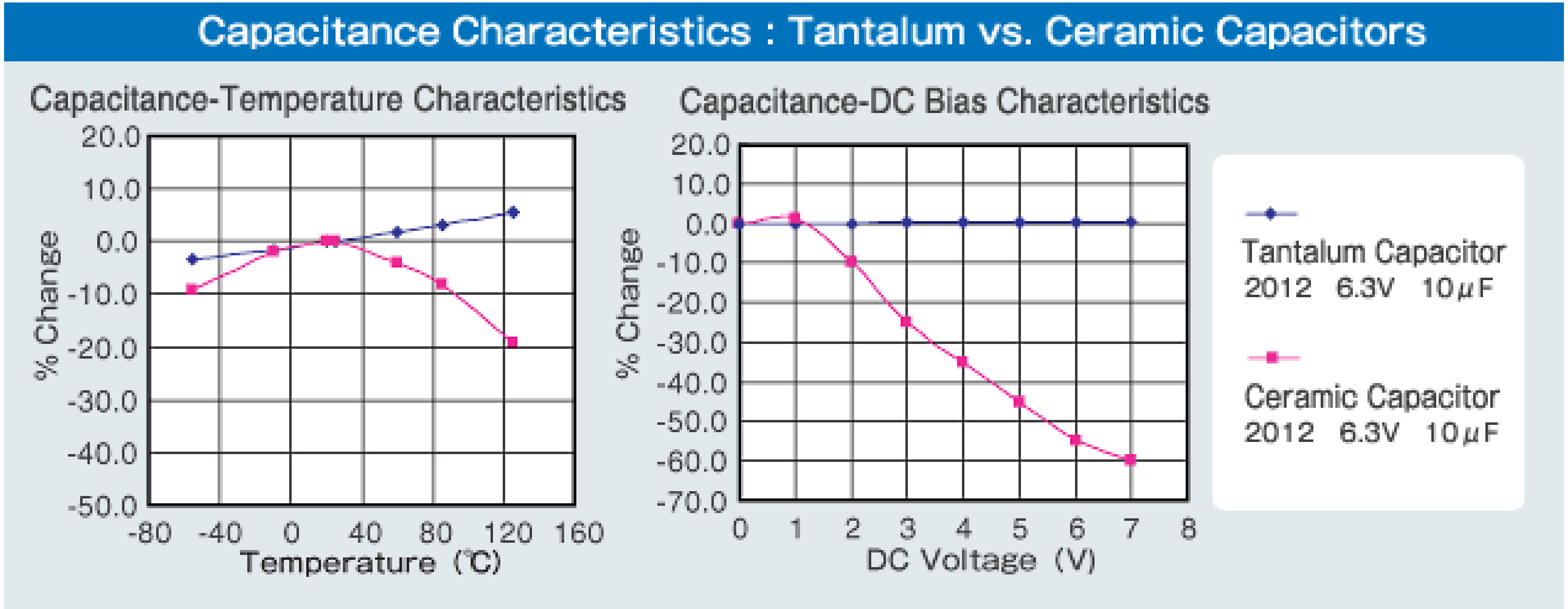


MLCC-Class 2 Dielectrics : DC Bias characteristics



Tantalum Vs MLCC

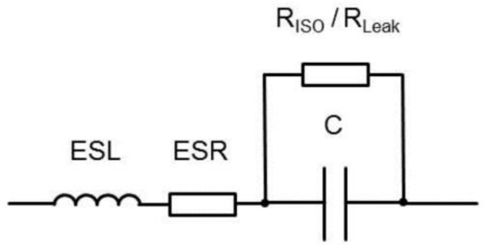




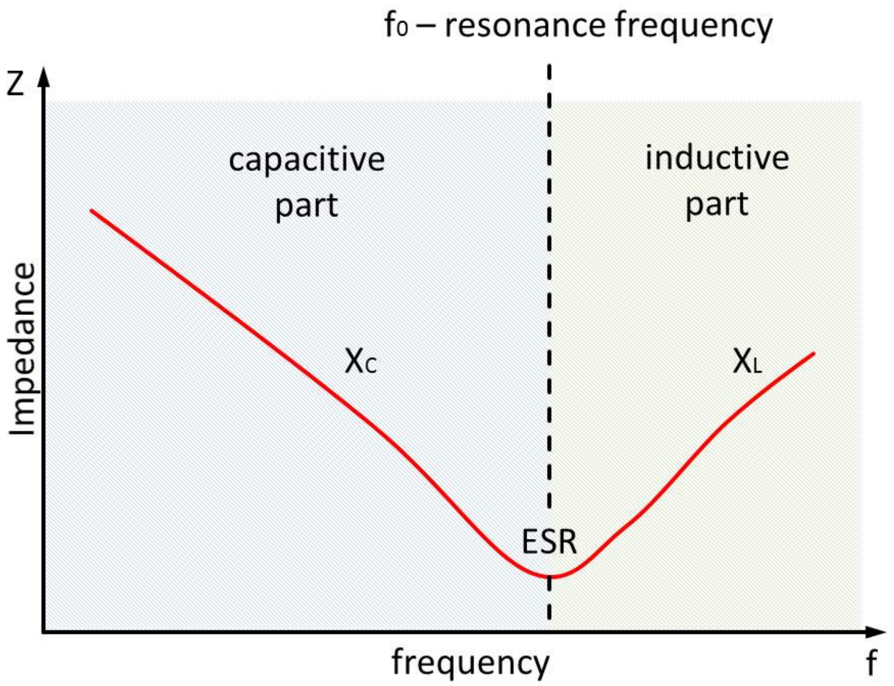
Equivalent circuit of capacitor

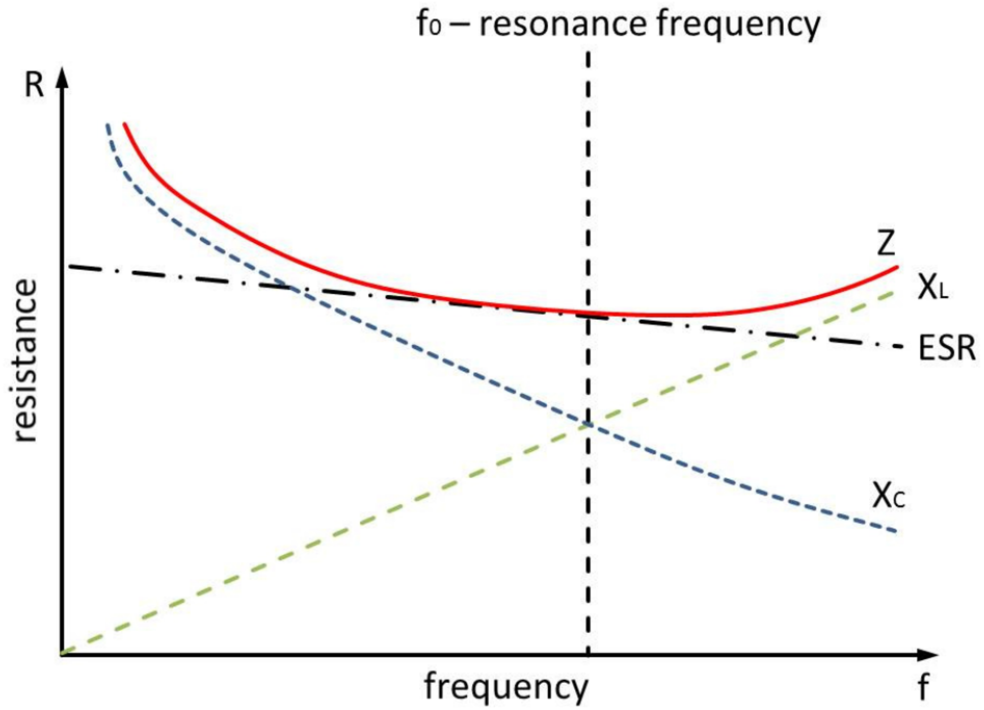
- ESR is the sum of in-phase AC resistance. It includes resistance of the dielectric, plate material, electrolytic solution, and terminal leads at a *particular frequency*.
- ESR acts like a resistor in series with a capacitor (thus the name Equivalent Series Resistance).
  - This resistance often is the cause of failures in capacitor circuits.
  - In case of SMPS, higher ESR output capacitor increases the ripple voltage.
  - In case of decoupling capacitors for digital power supply lines, higher ESR decreases the effectiveness of decoupling.
- ESL (Equivalent Series Inductance) is caused by the inductance of the electrodes and leads

Low ESR, ESL is critical for switching power supply output capacitors and decoupling capacitors



X_L, X_C, and Z curves of a capacitor

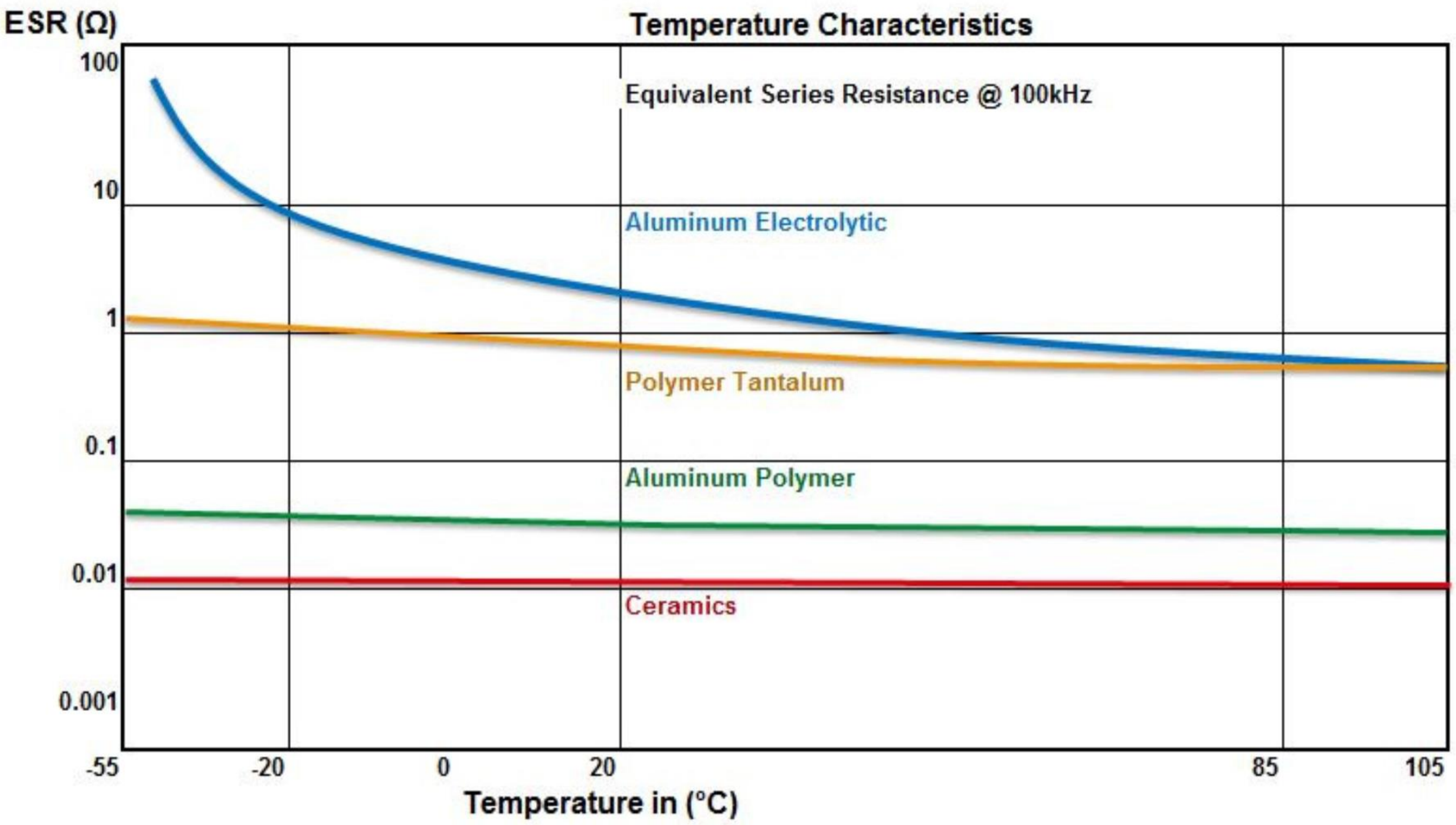




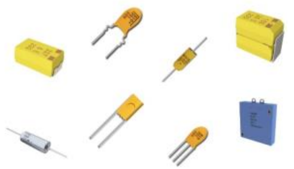
$$\omega L - \frac{1}{\omega C} = 0$$

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

ESR Range of capacitors

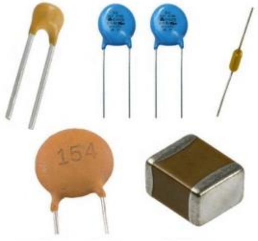


Aluminium Electrolytic



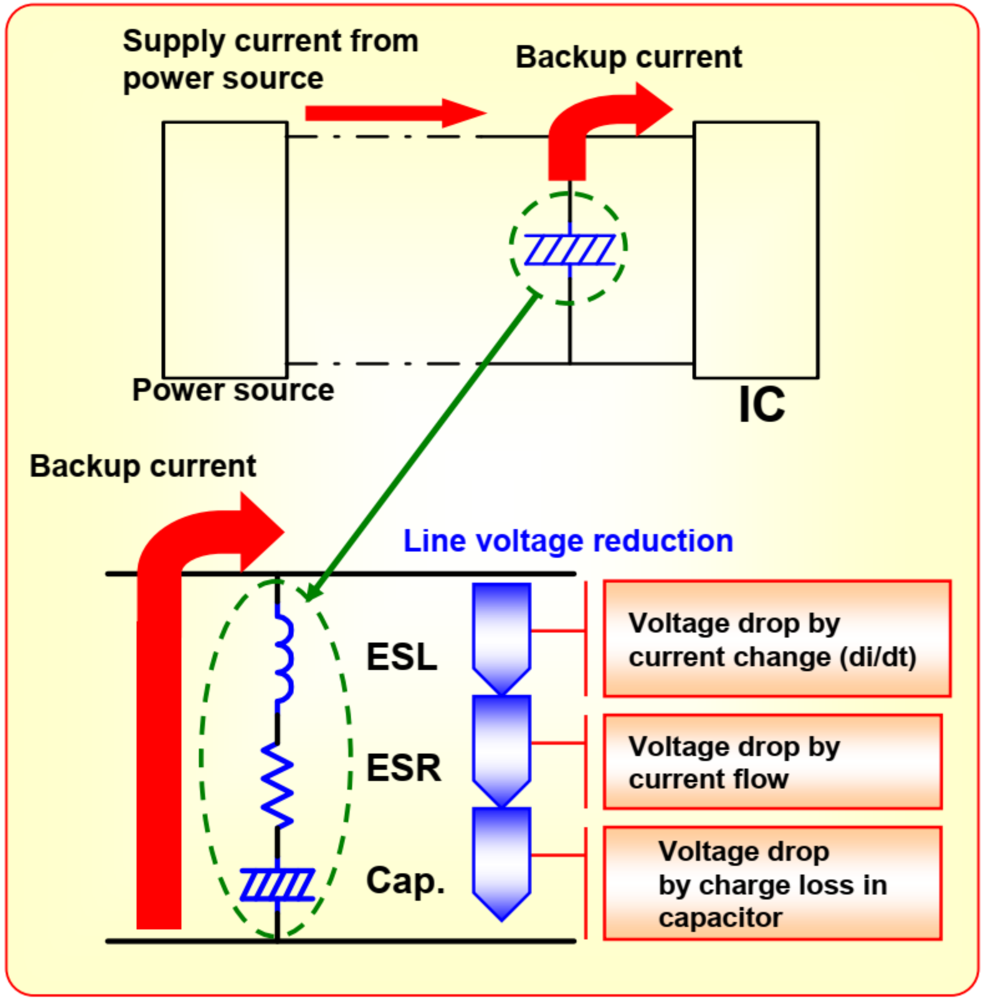
Polymer Tantalum

Aluminium Polymer



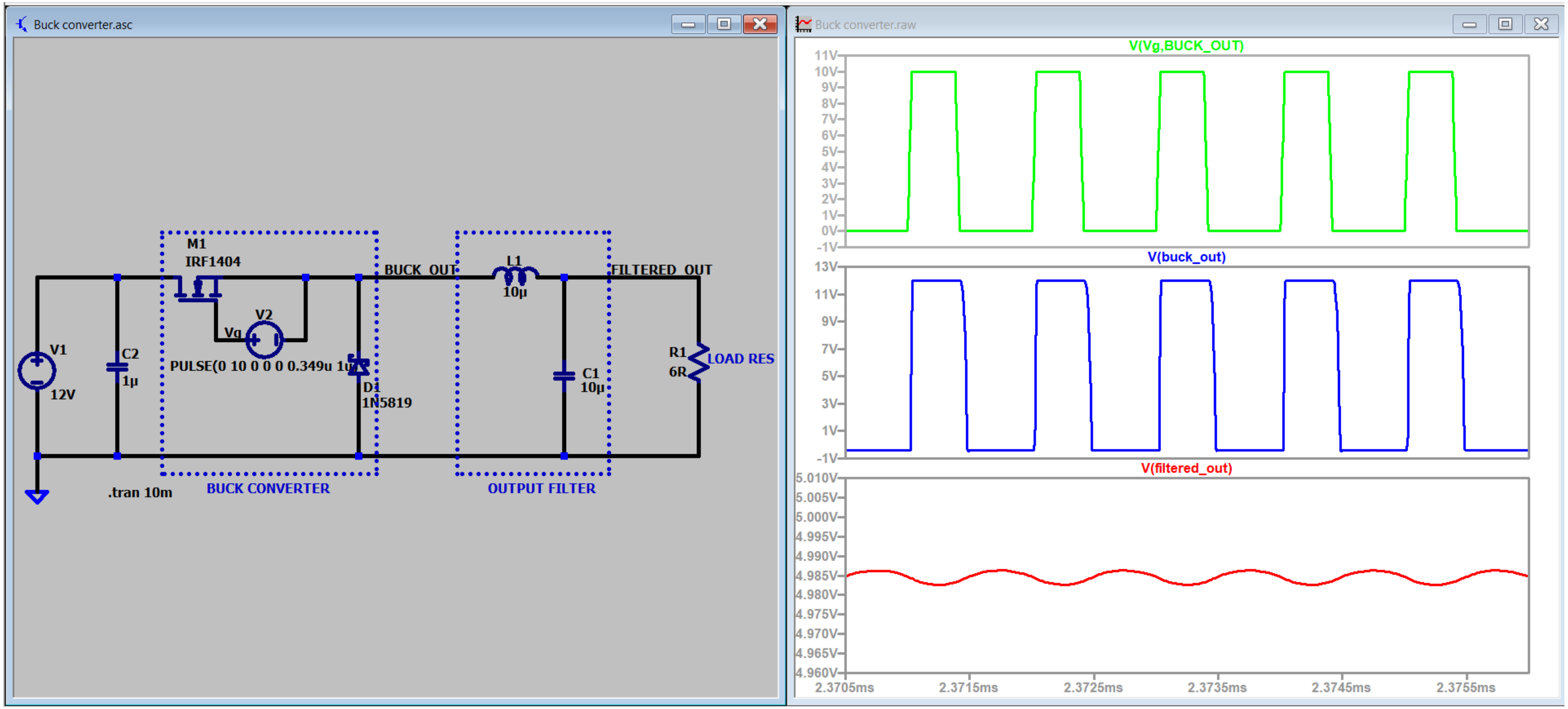
Ceramic / MLCC

Effect of C, ESR, ESL in decoupling application



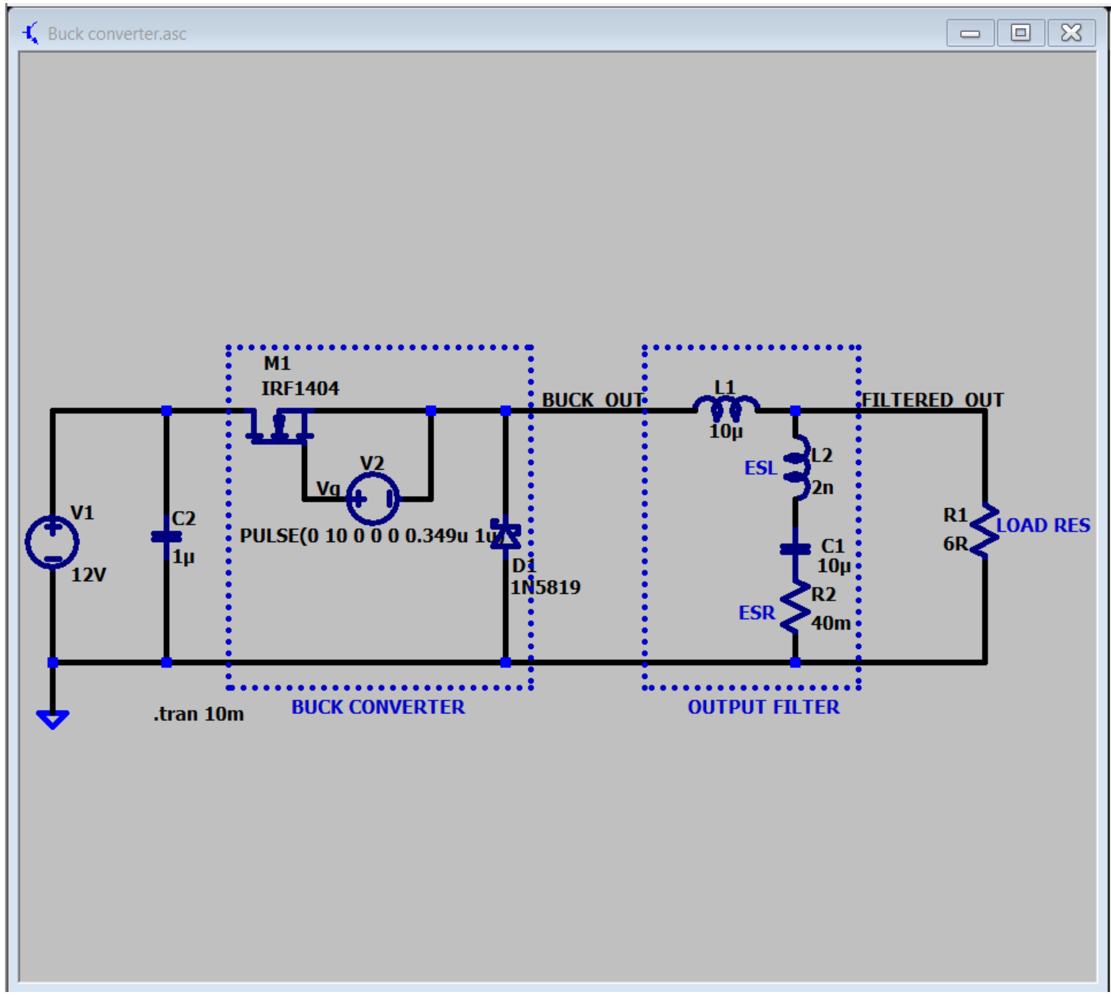
Low ESL	Support rapid current change
Low ESR	Voltage drop is small even through large current flows
Large capacitance	Reduce voltage drop for a long period of time

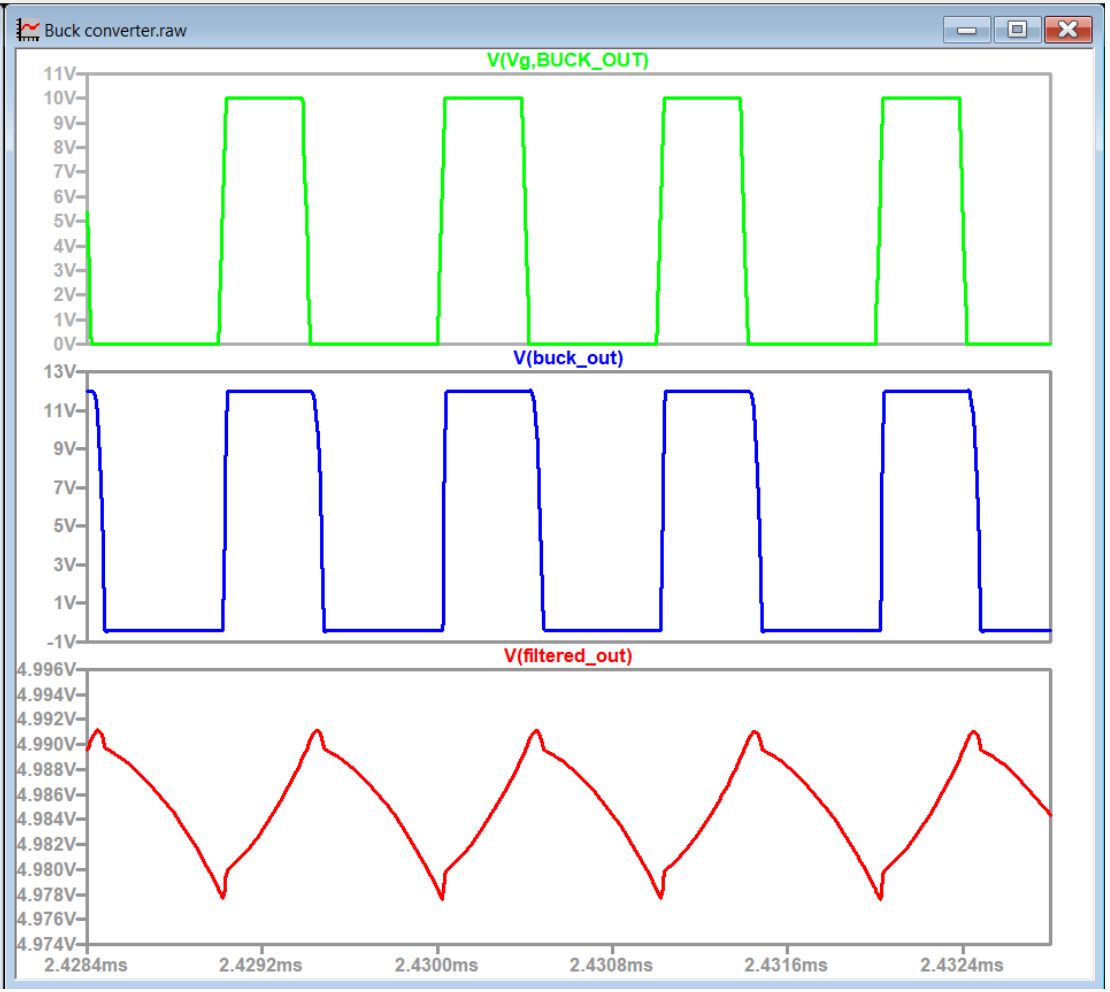
Buck converter ripple with ideal MLCC capacitor



With ideal capacitor – Filtered output Ripple only about 6mV

Buck converter ripple with actual MLCC capacitor





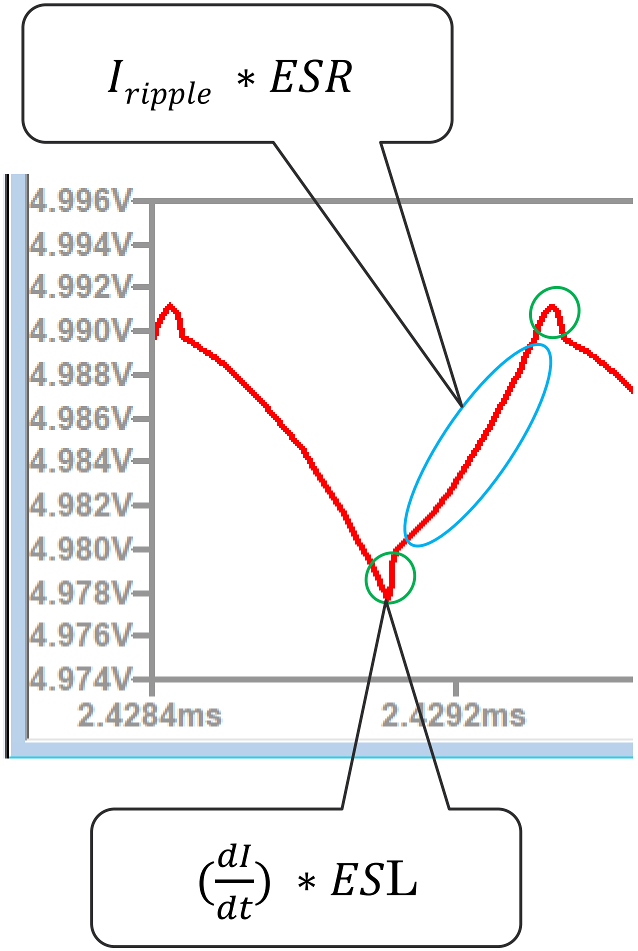
With actual MLCC capacitor comes ESR (40milli ohms) and ESL(2nH), which increases the output ripple now to 13mV.

Effect of ESR, ESL in power supply filter

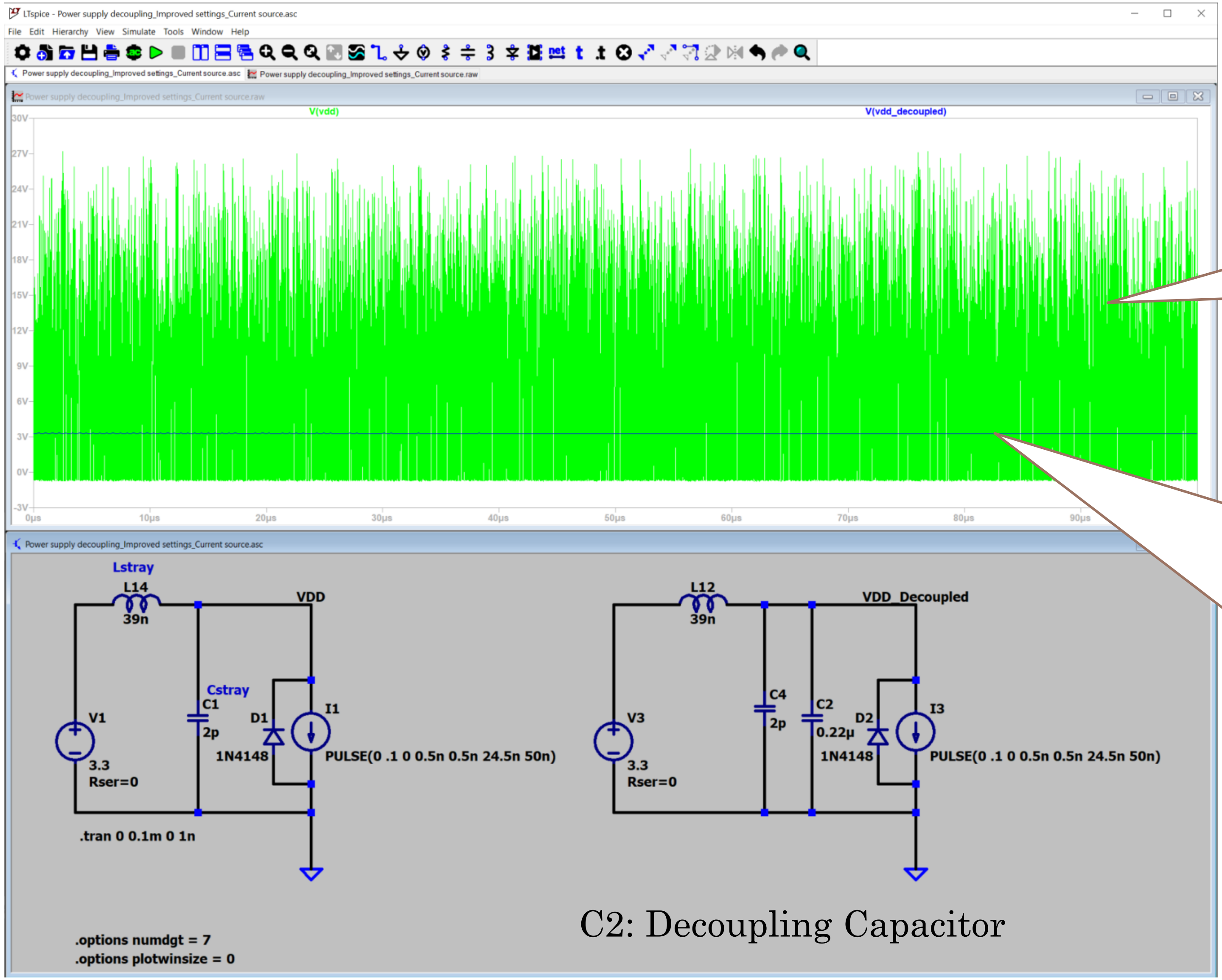
1) Ripple component due to insufficient filter capacitor value: This can be rectified using the appropriate value of filter capacitor. While using MLCC, Remember to compensate the loss of capacitance due to “DC bias”. Increase the capacitor value appropriately for compensation.

2) Ripple component due to ESR of the capacitor: MLCC caps has the lowest ESR as compared to Aluminum electrolytic capacitors and better as compared to Hybrid aluminum polymer capacitors. However, to further reduce the net ESR value consider using multiple MLCC caps in parallel as two equal resistors in parallel reduces the effective R to half.

3) Ripple component due to ESL: ESL of the capacitor causes the spikes or sometimes even high frequency oscillations affecting not just the ripple magnitude, even causing radiated EMI issues. Remember even the traces connecting the capacitor to inductor and the ground adds inductance due to PCB traces. Hence the connecting trace lengths need to be kept the least possible.



Decoupling MCU V_{DD} : Voltage Waveforms

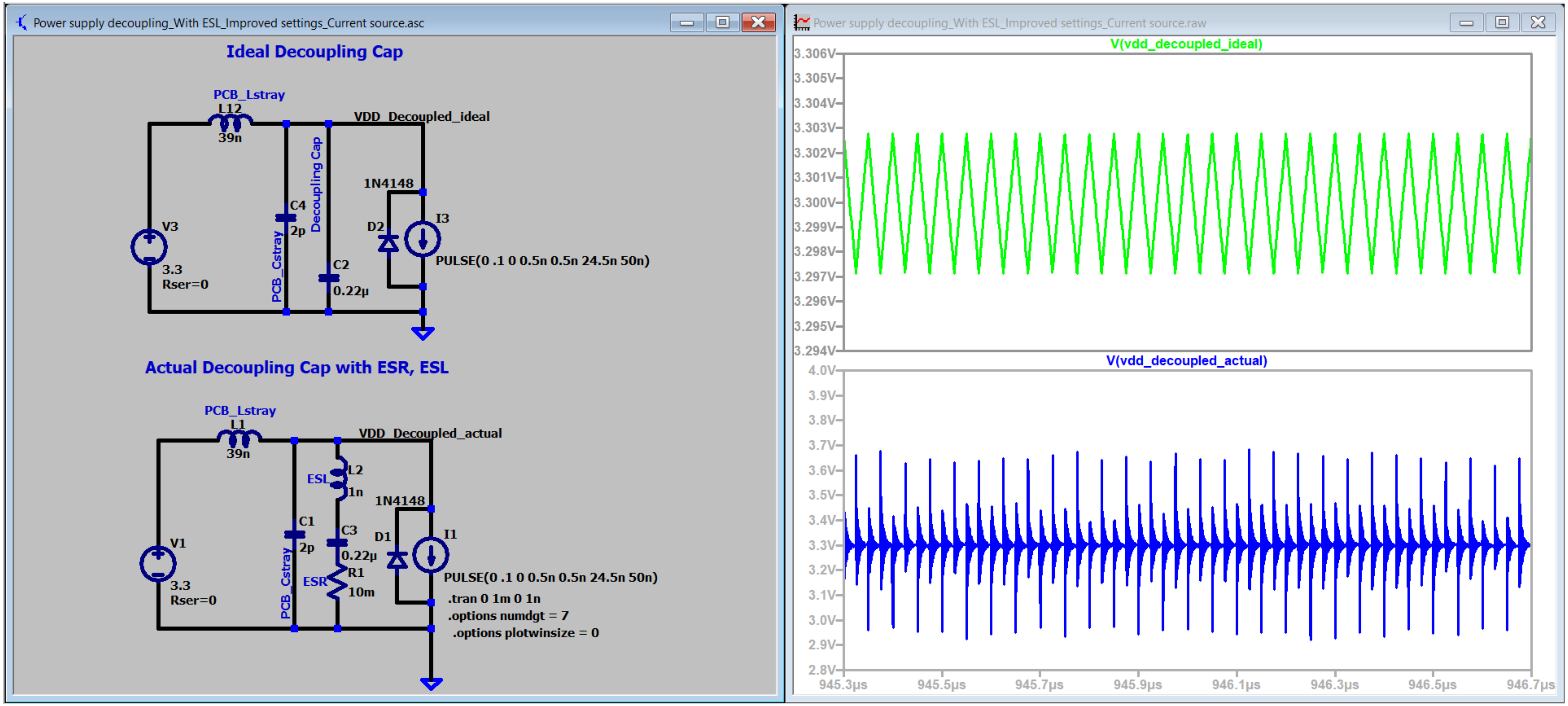


C2: Decoupling Capacitor

Green Trace: V_{DD} is highly noisy due to the counter emf (L*di/dt) generated by the trace inductance

Blue Trace: Addition of a 0.22uF cap close to the V_{DD} pin eliminates this noise, as the capacitor is able to supply the instantaneous current during switching transients, locally. Thus, decoupling the IC from the effects of trace inductance

Decoupling – Issues with ESL of decoupling cap



ESL of the decoupling capacitor impacts the decoupling effect severely. Hence it is important to use low ESL cap and very important to keep the connecting traces of this cap to MCU's VDD pin and ground, the least possible.

Decoupling V_{DD} : Trace length, Via

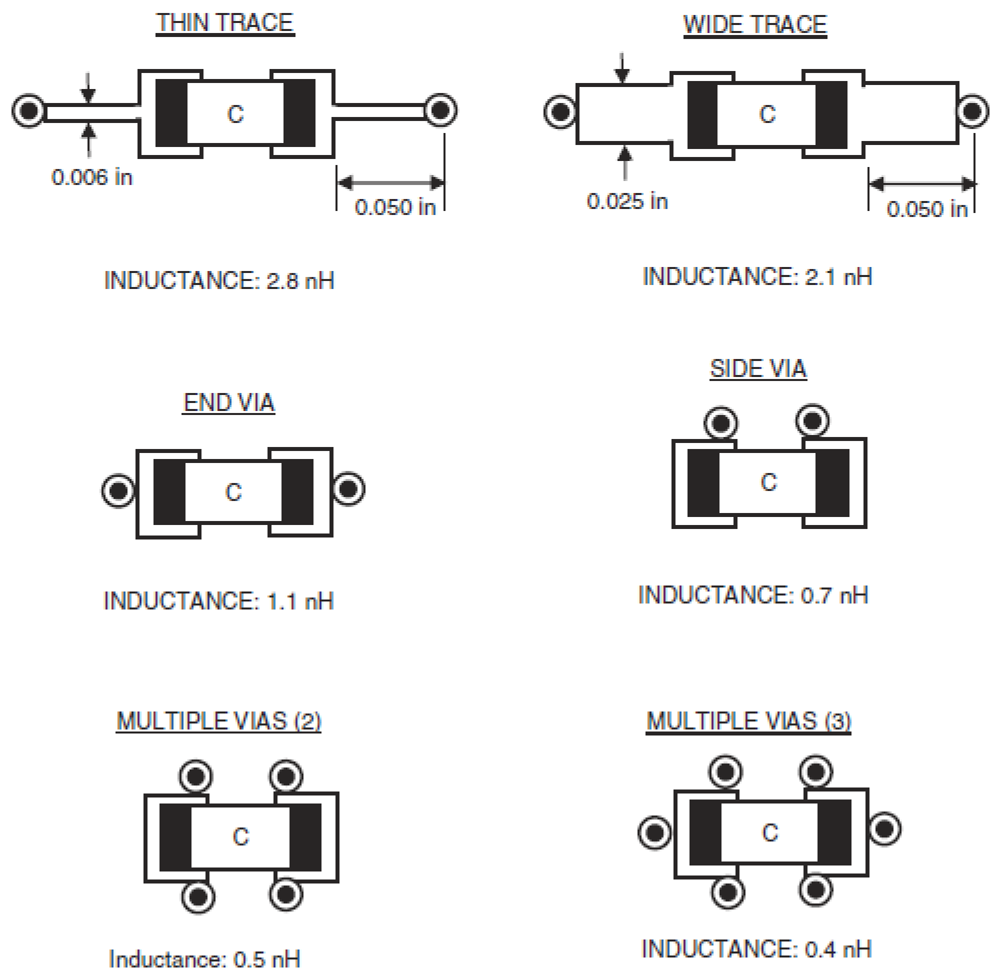
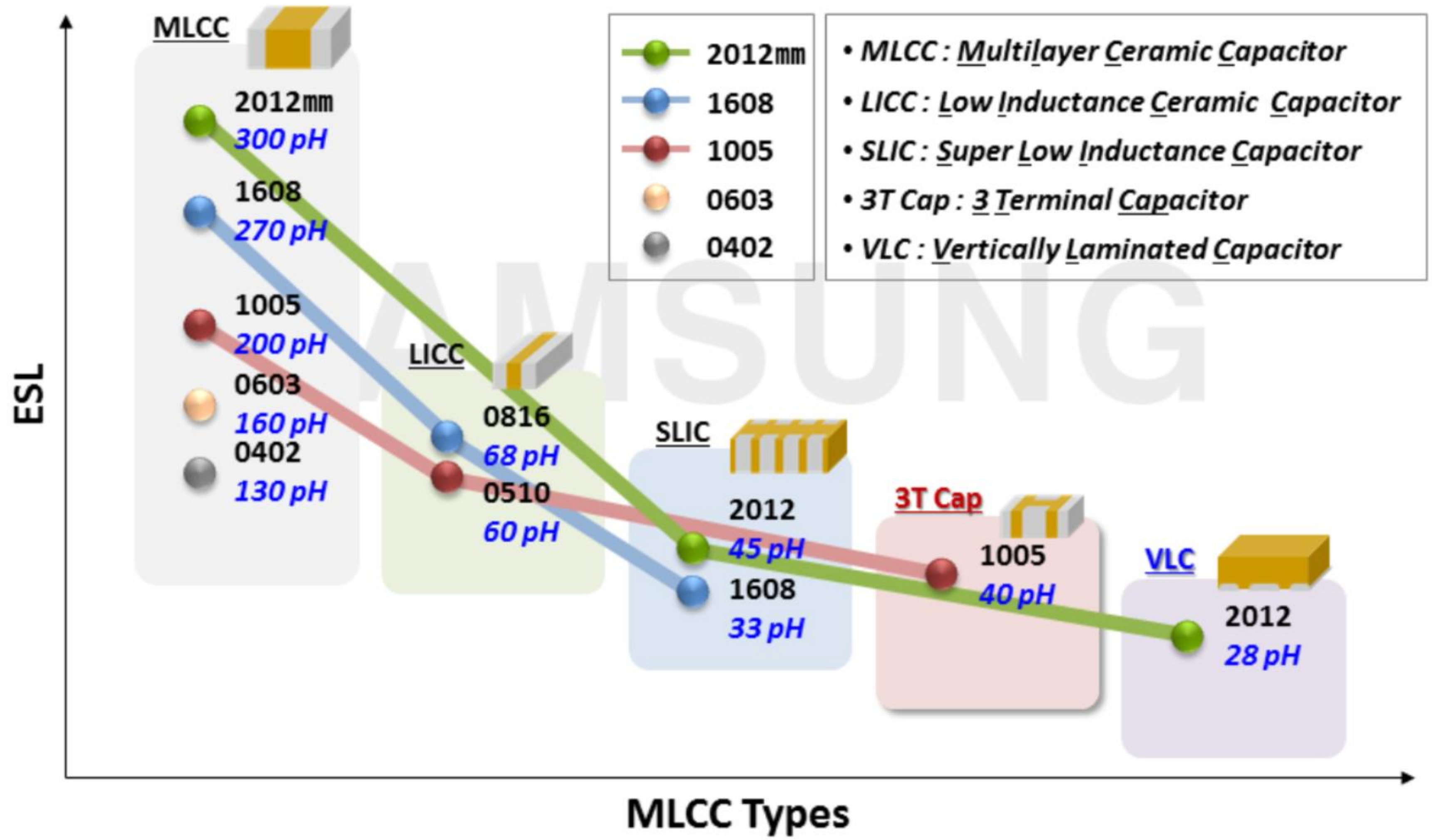


FIGURE 11-25. Inductance of various 0805 SMT decoupling capacitor mounting configurations.

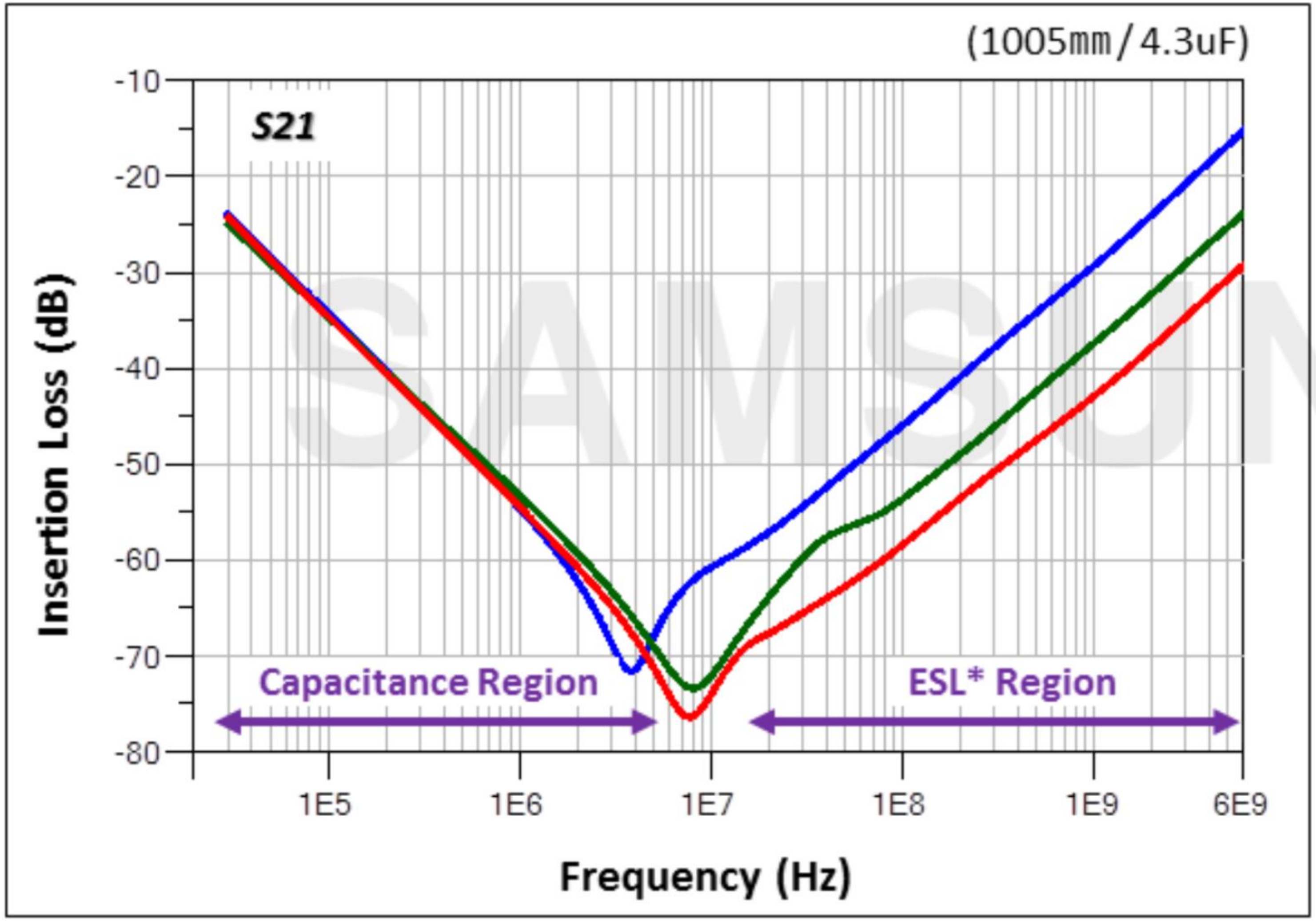
- There are very strict rules on the placement on decoupling capacitor.
- Rule #1: The decoupling capacitor must be placed right on the Vdd and Vss line of the IC supply to be decoupled. Ideally the connecting trace length should be less than 1 mm.
- Rule #2: Ideally, the decoupling capacitor and the IC should be on the same layer. If not, the connecting Vias will add stray inductance and hence placement of Vias and number of vias will be critical.

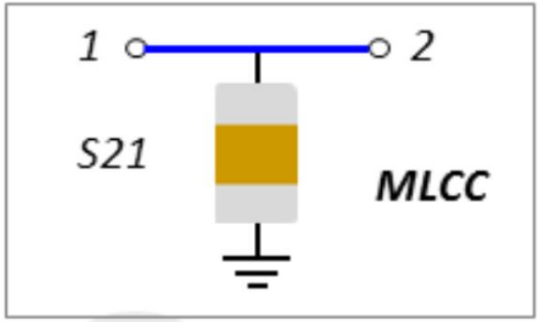
Comparison of inductance of Low ESL MLCCs

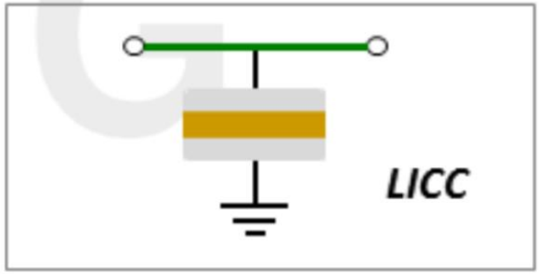


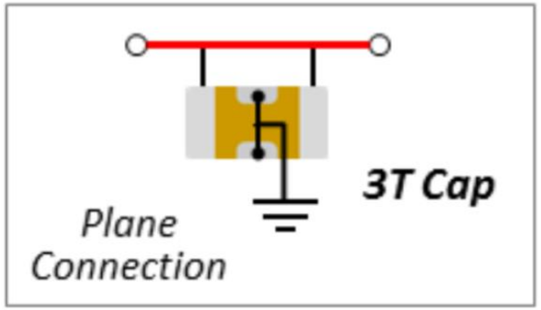
Courtesy: Samsung https://www.samsungsem.com/resources/file/global/support/product_catalog/MLCC.pdf

Frequency response of Low ESL caps



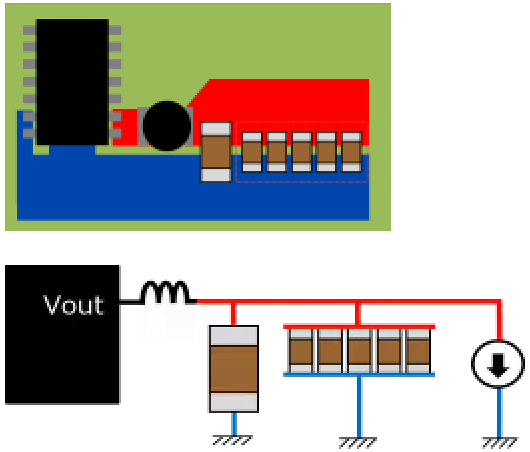


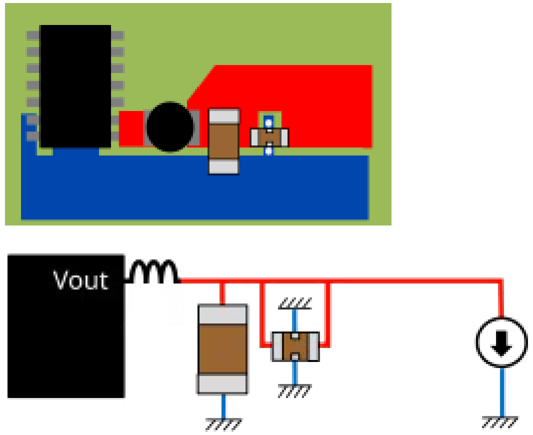


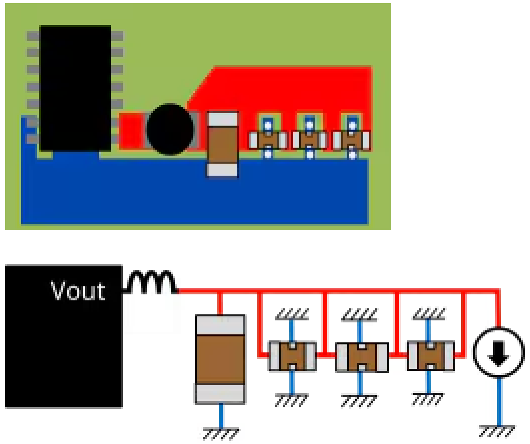


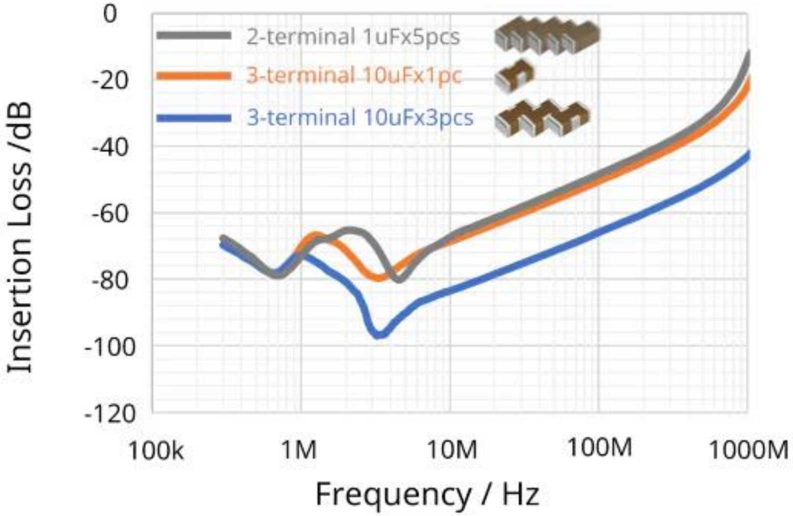
Courtesy: Samsung https://www.samsungsem.com/resources/file/global/support/product_catalog/MLCC.pdf

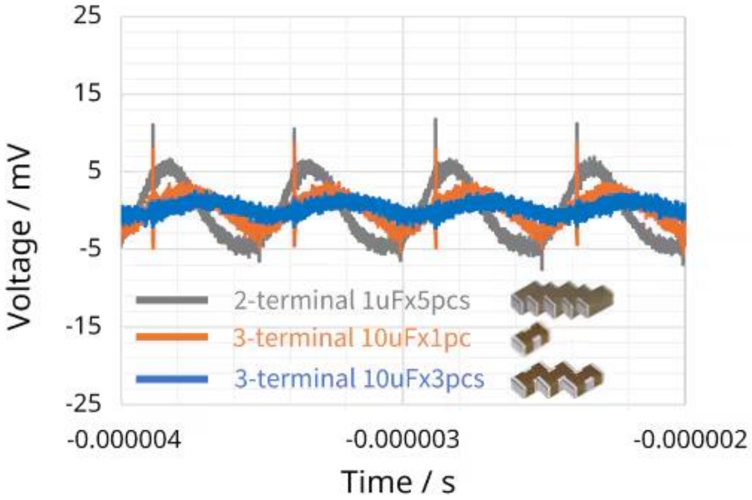
Comparison of Low ESL MLCCs





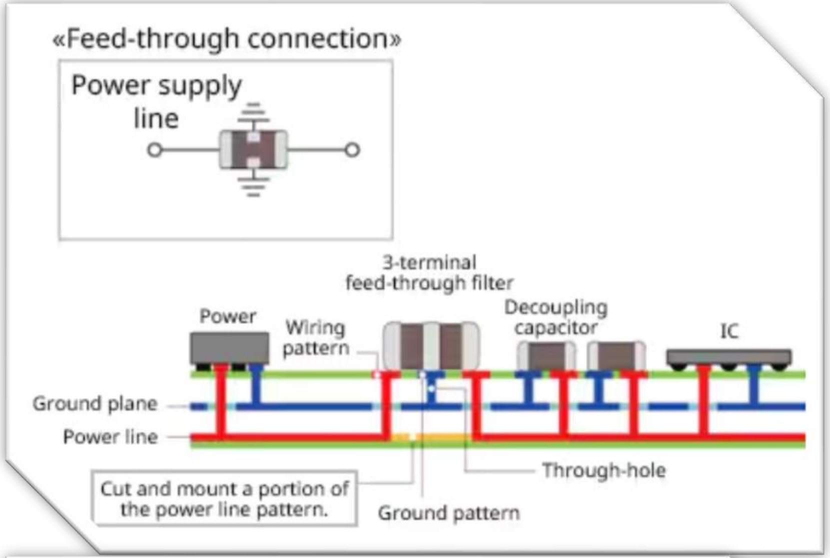


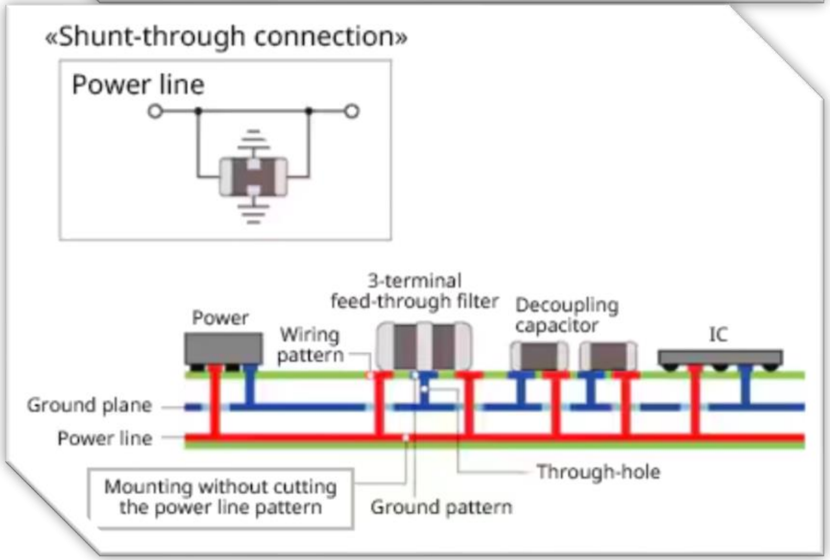




Courtesy: TDK https://product.tdk.com/en/techlibrary/solutionguide/yff-series.html

Circuit connection for 3 terminal caps

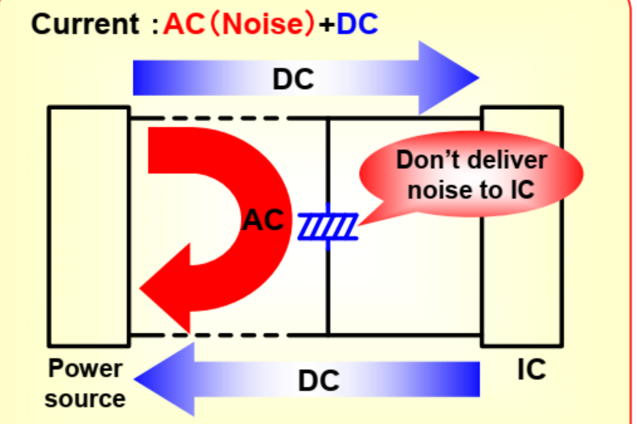




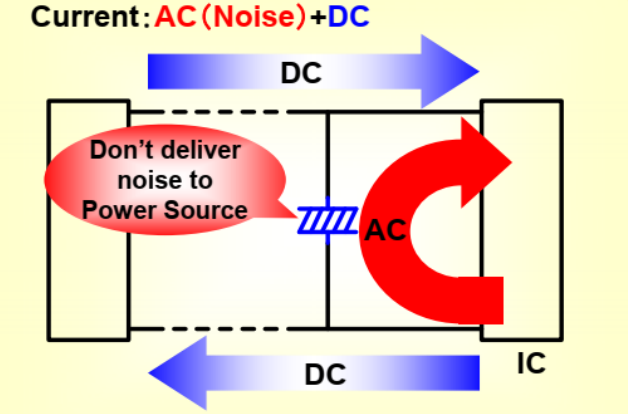
	Feed-through connection	Shunt-through connection
Mounting method	Cut a portion of the line pattern where noise needs to be removed and insert the filter.	Mount parallel (shunt) connection without cutting the line wiring pattern.
Main applications	Noise removal in high-frequency bands (filter applications)	Suppression of IC voltage fluctuation (decoupling applications)
Advantages	High noise removal effectiveness over a wide band up to high frequencies.	No rated current limitation as almost no current flows through the chip. Easy to change the number of components even after board design, as the wiring pattern is not cut.
Disadvantages	Rated current limitation due to current flowing through the chip. Design changes are difficult because the power line/signal line is cut.	Slightly higher ESL compared to feed-through connection.
Noise removal effectiveness	◎ Effectively dissipates noise to GND as noise on the line must pass through the chip.	○ Some noise passes through the power line, making noise removal less effective compared to feed-through connection.
Voltage fluctuation suppression effect	△ (Voltage drop occurs.)	◎ (Smaller voltage drop.)

Courtesy: TDK https://product.tdk.com/en/techlibrary/solutionguide/yff-series.html

IC Decoupling Vs Power supply bypass



Role of bypass capacitor

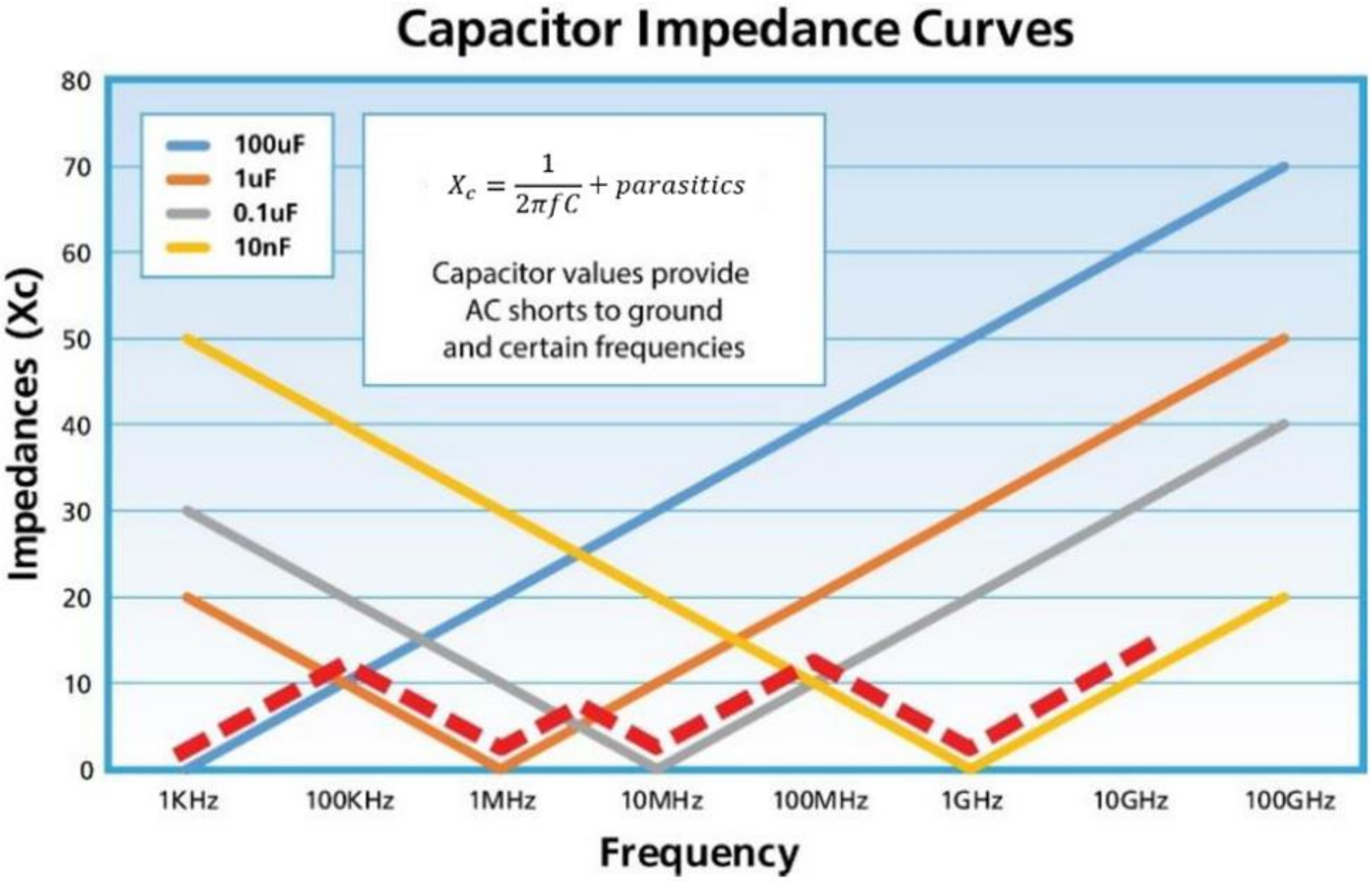


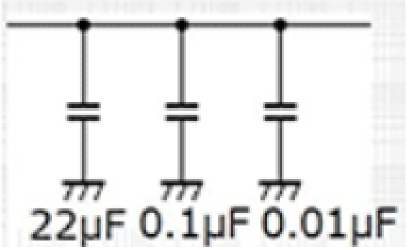
Role of decoupling capacitor

Bypass capacitor → Don't deliver noise from power source to IC

Decoupling capacitor → Don't deliver noise on IC to power source, etc.

Achieving low ESR for IC decoupling for wide f





Using capacitors of different values that are approximately a decade apart helps to have a lower level of ESR across a wide spectrum of frequencies which is essential in decoupling MCU, MPU based applications

Selecting MLCC caps using characteristics

For applications like "decoupling" and "Switch mode power supply filtering", it is essential to know the characteristics and parasitic elements of the capacitor for proper selection of the component and flawless circuit design.

There are few capacitor manufacturers, those who offer detailed characteristics of their capacitors for selection.

https://redexpert.we-online.com/we-redexpert/en/#/redexpert-embedded

https://ds.murata.co.jp/simsurfing/index.html?lcid=en-us

Use of Ferrite bead in decoupling multi rail power

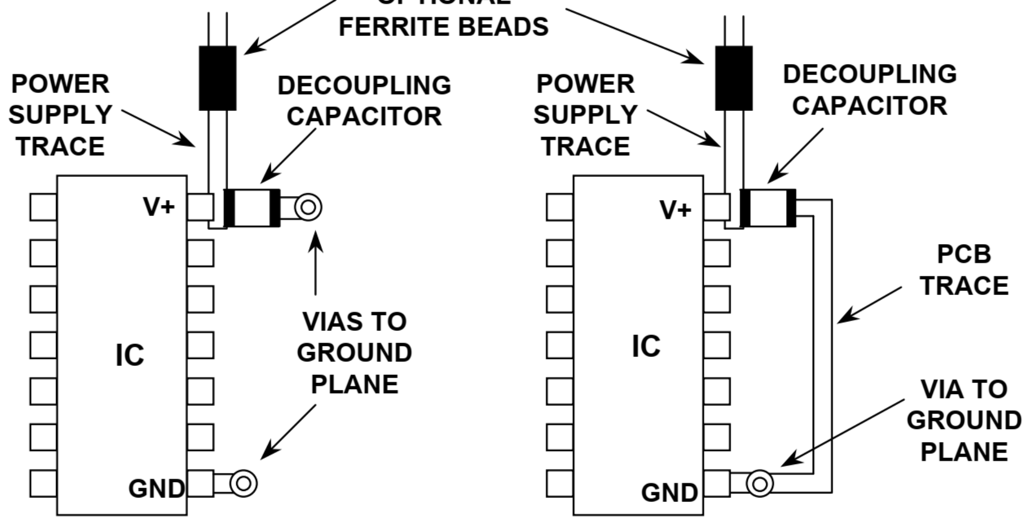


Figure 6: High Frequency Supply Filter(s) Require Decoupling via Short Low-Inductance Path (Ground Plane)

$$f = \frac{1}{2\pi\sqrt{LC}}.$$

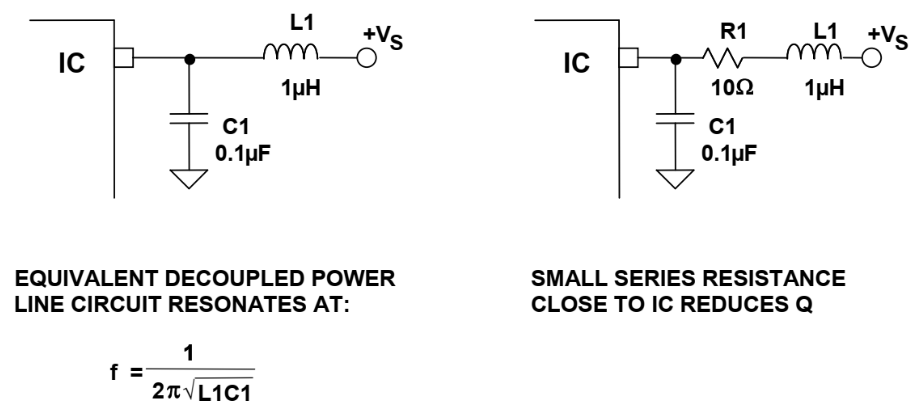


Figure 7: Resonant Circuit Formed by Power Line Decoupling

When a single power supply supplies power to different MCUs or MCU and analog, Use of a ferrite bead is essential to ensure the noisy power section of the circuit such as MCU doesn't affect rest of the other power paths.

Calculating decoupling capacitor requirement

Calculate Capacitor requirement

- Line Inductance (L): 5uH
- Pulse current (di): 0.1 Amps
- Tolerable drop in voltage (dV) – 20mV
- $C = \frac{L}{\left(\frac{dV}{di}\right)^2} = \frac{5}{\left(\frac{0.02}{0.1}\right)^2} = 125\text{uF}$

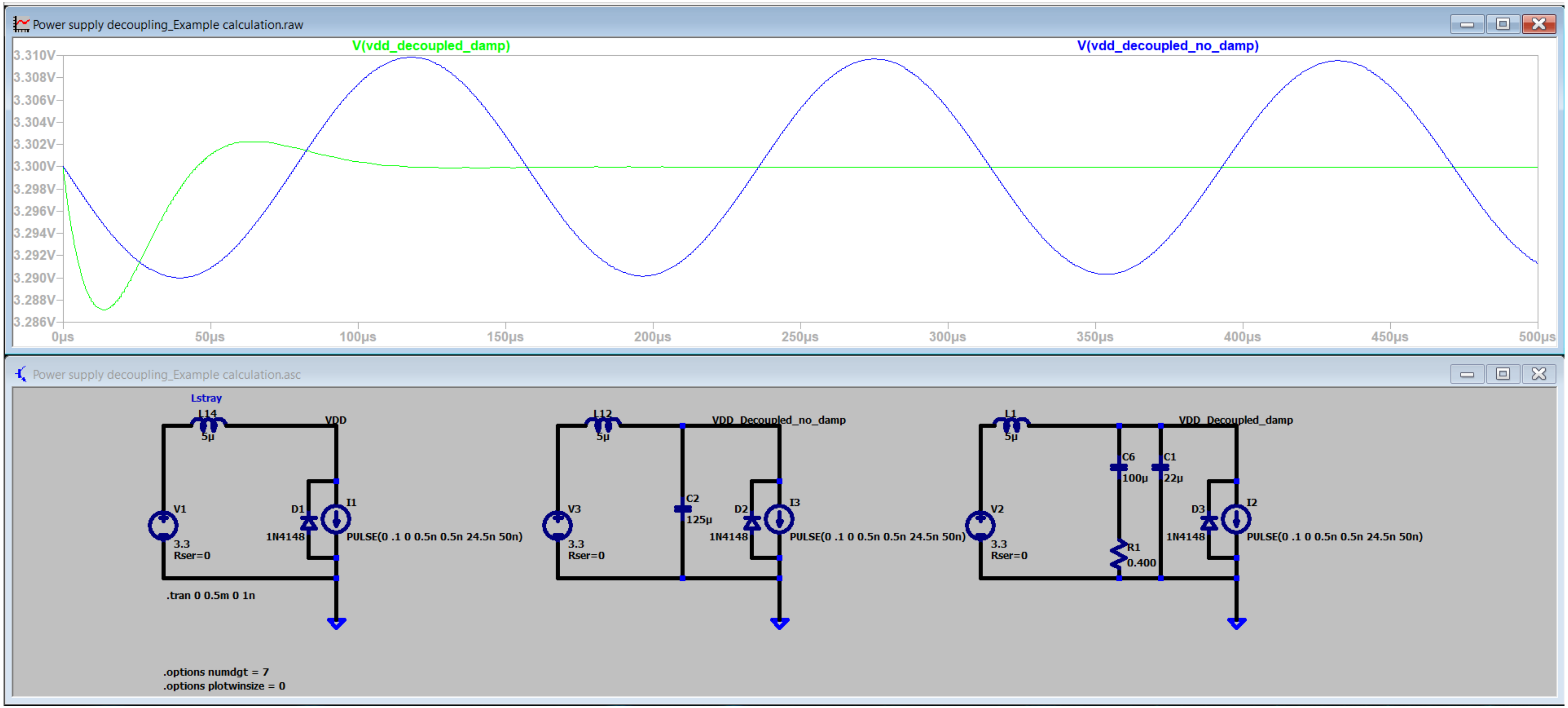
Calculate Damping Resistor

- $\zeta = \frac{R}{2} * \text{sqrt}\frac{c}{l}$
  - Damping factor of 1: Critical damping
  - Damping factor less than 1: Under damped
  - Damping factor greater than 1 : Over damped
  - Ex: ζ = 1; C 125uF; L = 5uH
- $R = sqrt\frac{l}{c} * 2 * \zeta = 0.4$ Ohms

Often the combination of L and C acts as a resonant circuit and can causes oscillation. Hence, it is necessary to reduce the "Q" of the resonant circuit using a Resistor. This can be connected in series with the capacitor

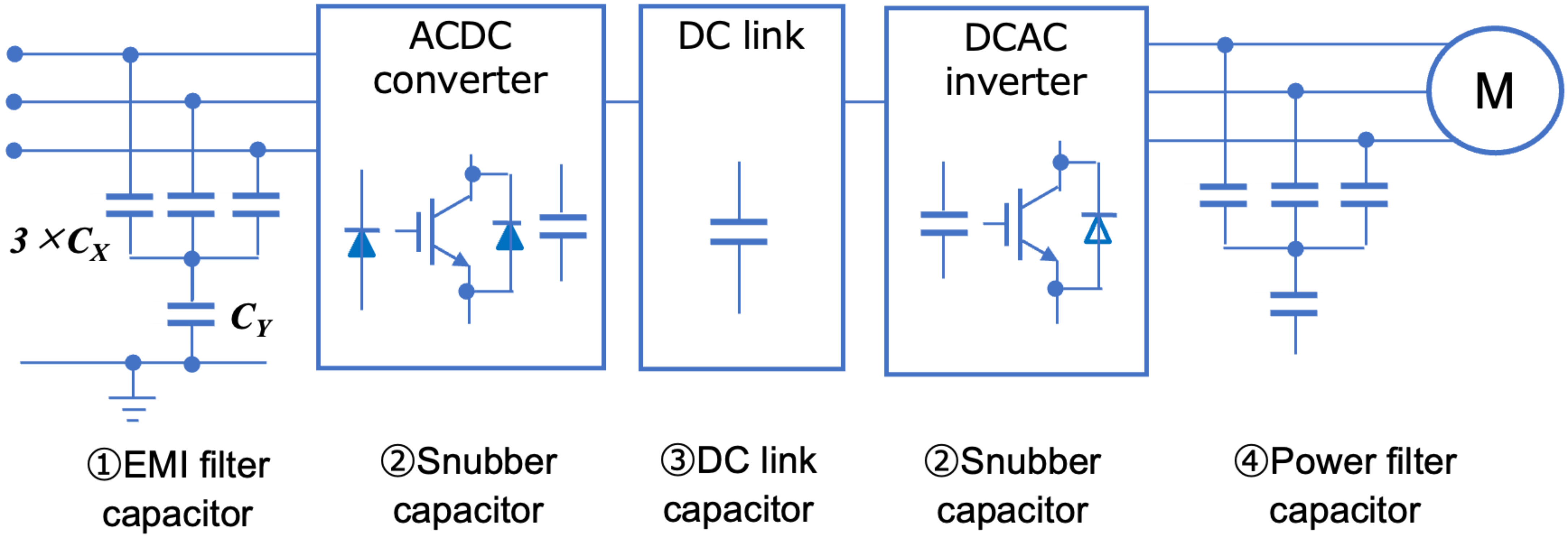
Courtesy: https://www.youtube.com/watch?v=eS5Ma4ET-sY&t=0s

Decouple with damping for higher line inductance



Instead of 125uF, here we have used one 100uF cap in series with 0.4 Ohms and another 22uF in parallel for better decoupling

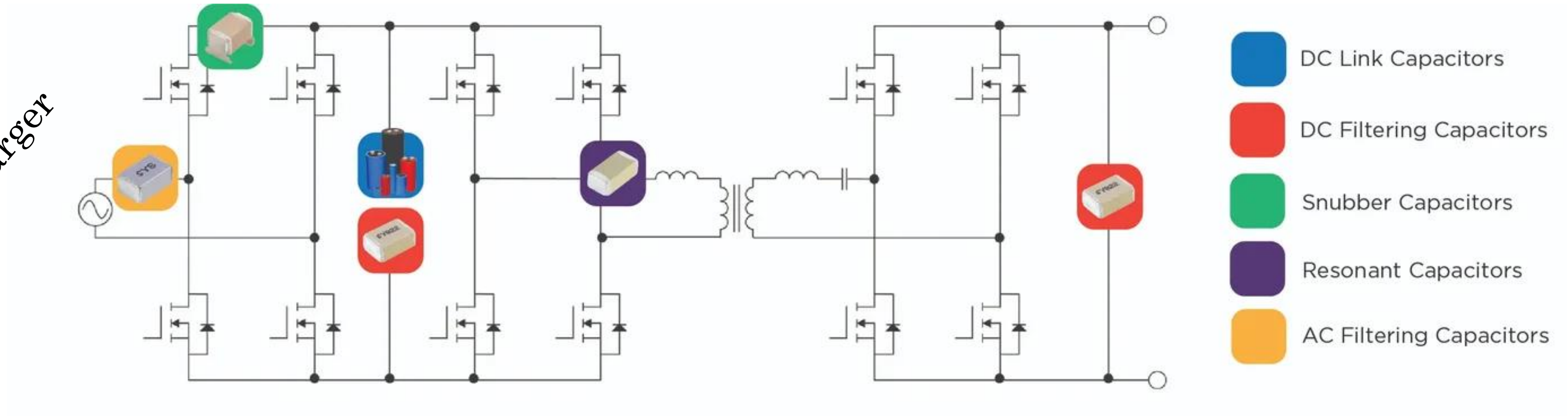
Capacitors in power electronics (Motor Drive)



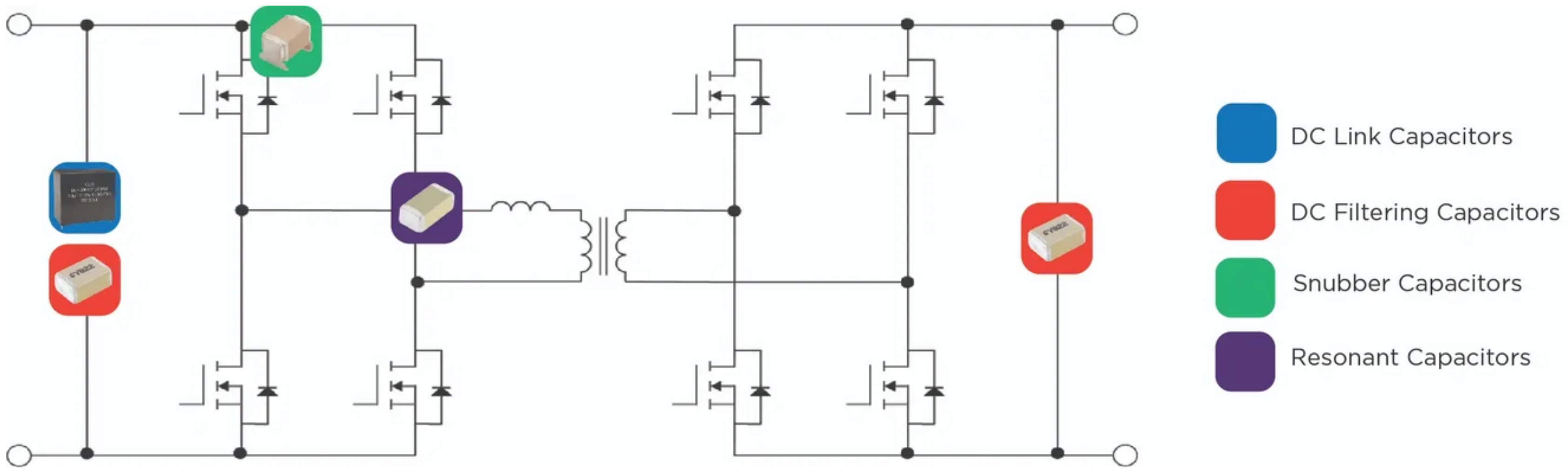
Courtesy: https://www.aictech-inc.com/en/valuable-articles/capacitor_appllication01a.html#dl-pdf

Capacitors in Automotive electronics

Automotive
On-Board Charger



Automotive DC-
DC Converter



Courtesy: https://blog.knowlescapacitors.com/blog/exploring-the-capacitor-technologies-needed-in-electric-vehicles

DC Link Capacitor selection

- Combining different types of capacitors (e.g., film and electrolytic) can offer advantages in terms of performance, life, and cost.
- Combining high-voltage MLCCs and film capacitors in a DC-link design offers advantages like improved high-frequency performance and reduced overall capacitor size. MLCCs excel at high-frequency applications and filtering, while film capacitors provide the necessary bulk capacitance and high-voltage capability.
- Film capacitors are typically available with high voltage ratings, making them suitable for high-voltage DC-link designs. Film capacitors are typically available with high voltage ratings, making them suitable for high-voltage DC-link designs.

Courtesy: https://www.aictech-inc.com/en/valuable-articles/capacitor_appllication01a.html

DC Link Capacitor Hold up value Calculation

- To calculate the hold-up capacitance required for a DC bus, we need to determine the capacitance that can supply the load current during an interruption while ensuring the DC bus voltage does not drop below the allowable limit.
- V_{avg} is the average voltage during discharge, approximated as:

$$V_{avg} \approx \frac{V_{bus}+V_{min}}{2} = \frac{400+360}{2} = 380\,\text{V}$$

- *Energy required by the load during the interruption*
- $E = P \times t = V_{avg} \times I_{load} \times t = 380 \times 10 \times 0.1 = 380\,\text{J (joules)}$
- Equate the energy required by the load to the energy to be provided by the capacitor:

$$\frac{1}{2}C(400^2 - 360^2) = 380\ Jules$$

$$C \times 15{,}200 = 380\ \text{Jules}$$

$$C = \frac{380}{15{,}200} = 0.025\,\text{F} = 25{,}000\,\mu\text{F}$$

Given Parameters:

- DC Bus Voltage (V_{bus}): 400 V
- DC Bus Load Current (I_{load}): 10 A
- Interruption Time (t): 0.1 s
- Allowable DC Bus Drop: 10% of V_{bus}
  - Allowable voltage drop = $0.1 \times 400 = 40\,\text{V}$
  - Minimum allowable voltage (V_{min}) = 400 – 40 = 360 V

Ripple current rating of capacitor

- Current through the capacitor (Ripple current)creates self-heating of the capacitor which is calculated by
  $$\Delta T = (Irms)^{2} \cdot ESR \cdot Rth$$
- The thermal resistance (R_{th}) between a capacitor and the environment is a function of the airflow over the capacitor, the surface area of the capacitor, and any heat sinking of the capacitor.
- Power loss generates self-heating of the capacitor. Depending on the capacitor technology this can lead to reduction of lifetime or in worst case the capacitor can fail.
- According to EIA-809, the ripple current can be calculated with: $I_{max} = \sqrt{(P_{max} / ESR)}$
- P_{max} is the maximum Power rating of the capacitor and the ESR is the equivalent series resistance of the capacitor which depends on the frequency and the temperature.
- Using capacitors in parallel can help to carry more ripple current as per application requirement and also helps to reduce the temperature rise in capacitor and thereby improves life.

AC Current Rating

$$I_{max} = \sqrt{\frac{\Delta T_{max}}{R_{th} \text{ X } ESR}}$$

I_{max}: Maximum allowable rms value of ripple current (Ω)

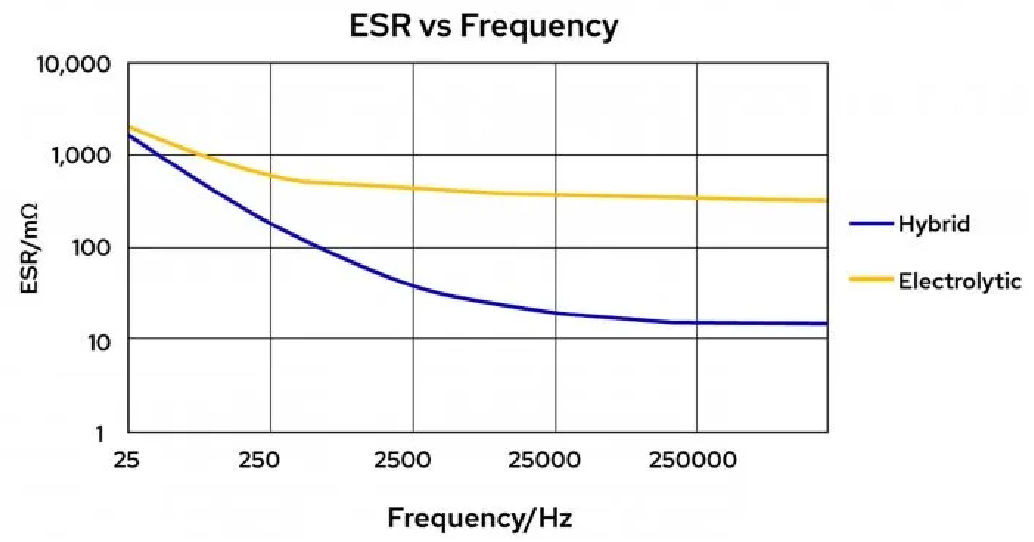
ESR: Serial equivalent Resistance
R_{th}: Thermal resistance of capacitor (°C/ W)
ΔT_{max} :Maximum allowable temperature rise (°C)

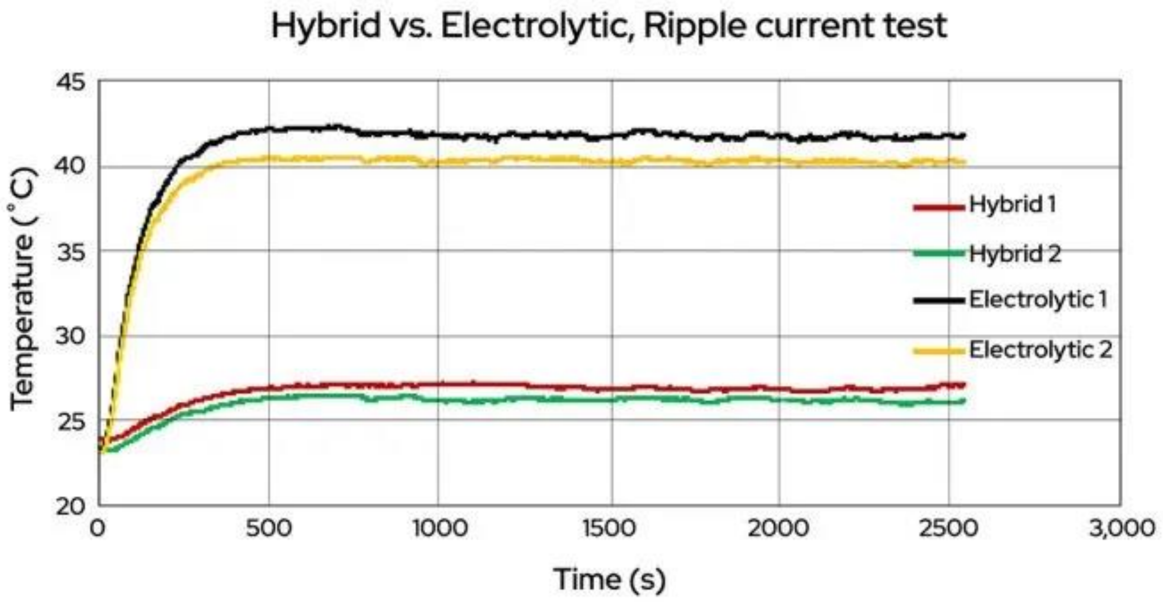
Power dissipation

$$P_{max} = \frac{\Delta T_{max}}{R_{th}}$$

Courtesy: Key Parameters for Designing Ceramic Capacitors in SMPS Circuits

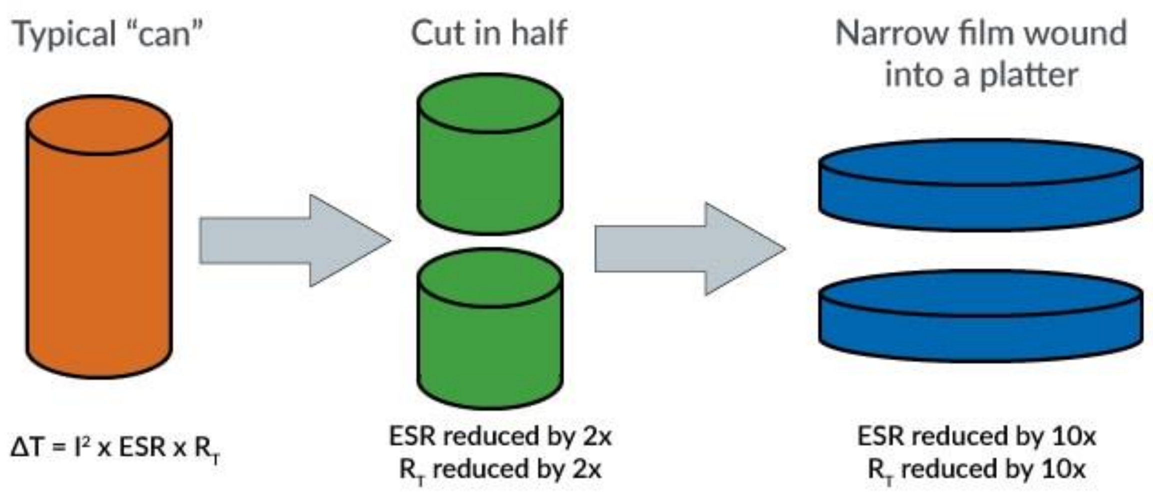
Ripple current rating: Aluminum Polymer Hybrid Vs Electrolytic

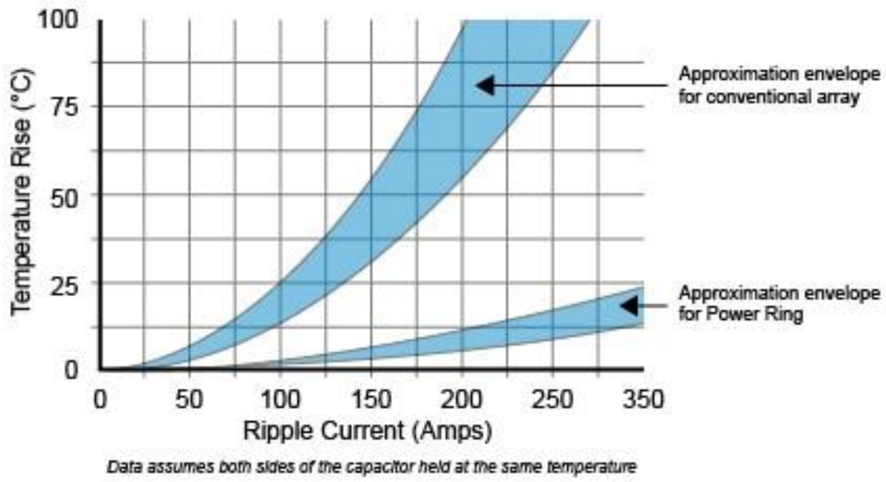




Courtesy: https://www.edn.com/ev-designs-employ-electrolytic-capacitors-to-leverage-ripple-current/

Ripple current : Power ring capacitors





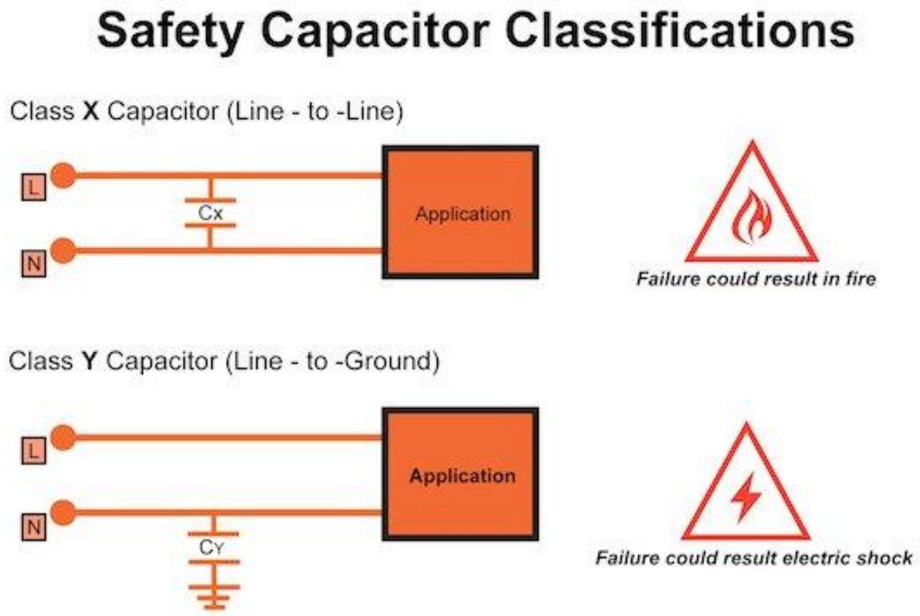
Courtesy: [Best DC Link Capacitor? Power Ring from Advanced Conversion]

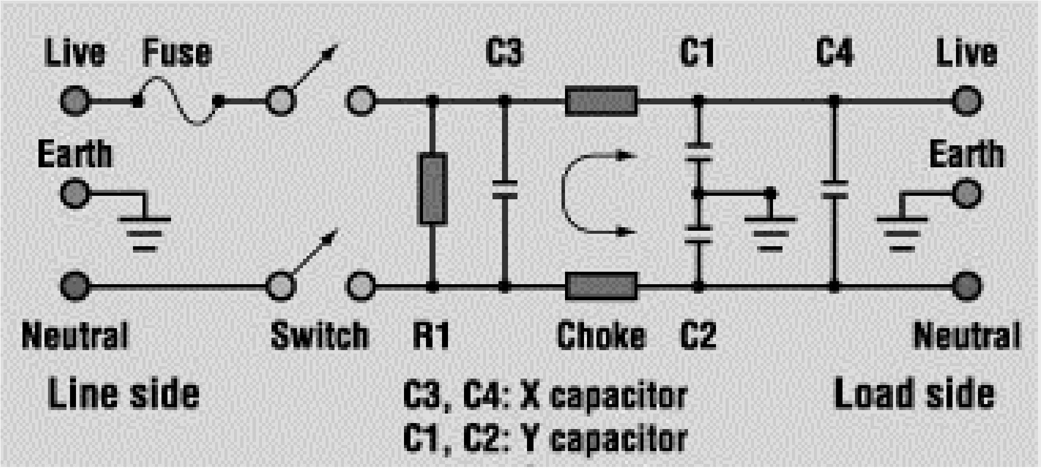
EMI filter capacitors

- Capacitors are needed in power line EMI filters.
- **Polypropylene capacitors** corresponding to the safety standards are preferred for withstanding 4kV and 2.5kV are designated as "X1" and "X2", respectively, and have a capacity of several μF to meet EMI standards.
- Capacitors that attenuate common mode emissions from line to ground are "Y1" type with 8kV rating and "Y2" type with 5kV rating. These capacitors are primarily **film capacitors**, and their low ESL characteristics allow them to maintain high self-resonance.

Subclass (IEC 60384-14)	Rated Voltage
Y1	≤500VAC
Y2	150VAC≤ V <300VAC
Y3	150VAC≤ V <250VAC
Y4	<150VAC

Subclass (IEC 60384-14)	Peak Voltage Pulse (while in service)
X1	>2.5kV ≤4.0kV
X2	≤2.5kV
X3	≤1.2kV





X and Y Rated Capacitors

- Y-class capacitors are safety capacitors used to prevent hazardous voltage from reaching the user through the enclosure of electronic equipment. They are divided into Y1, Y2, Y3, and Y4, each with different rated AC voltages and peak test voltages.

- X1, X2, and X3 capacitors are classified based on their ability to withstand peak voltage pulses during AC line operation.
- X1: primarily used as AC input EMI filters
- X2 : used for high voltage snubber circuits
- X3 : used in snubber circuits

Class	Rated voltage	Impulse voltage	Insulation bridging	May be used in primary circuit
Y1	250Vac	8000V	Double or reinforced	Line to protective earth
Y2	250Vac	5000V	Basic or supplementary*	Line to protective earth
Y3	250Vac	None	Basic or supplementary	-
Y4	150Vac	2500V	Basic or supplementary*	Line to protective earth
X1	250Vac	4000V	-	Line to line
X2	250Vac	2500V	-	Line to line
X3	250Vac	None	-	Line to line

Capacitors for Snubber circuit

- Capacitors can be used to slow down the switching waveform to reduce stress on semiconductors caused during switching transients. Capacitor for this application is referred to as Snubber Capacitor

- This application requires the ability of capacitor to withstand high voltage pulses (dV/dt). For example, the dV/dt across the drain to source of the MOSFET needs to be suppressed to avoid failure due to overvoltage, violating the V_{DD} specification.

- Film capacitors made of polypropylene are effective for this purpose. Snubber capacitors are combined with a resistor in series to limit the current during discharge and also to damp any unwanted resonance due to parasitic L, C in the circuit

- For low loss RCD snubber is used.

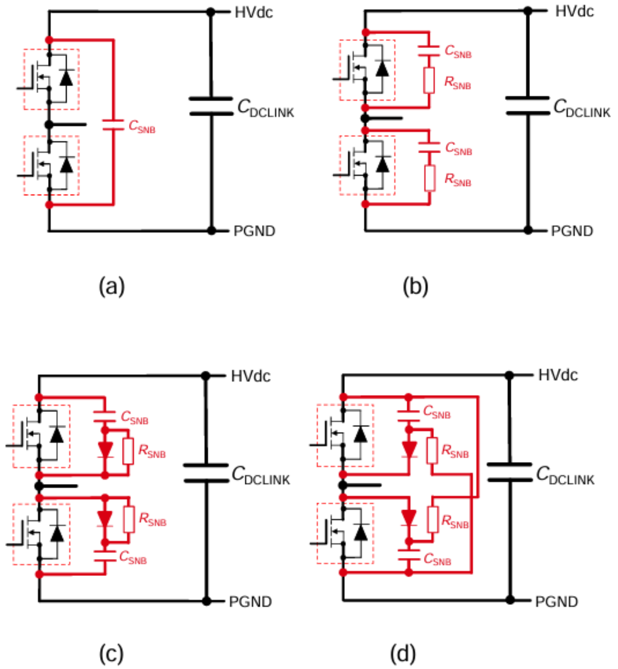
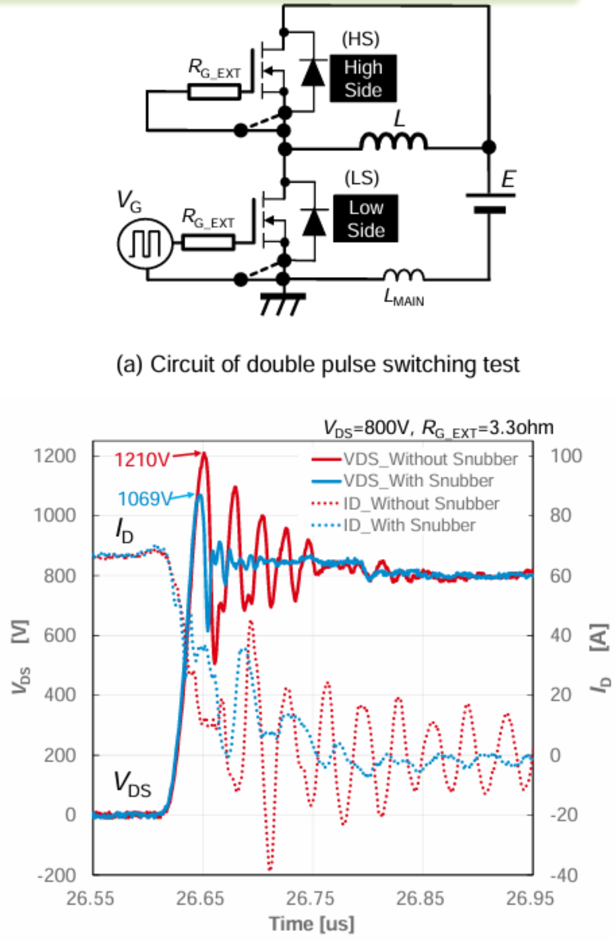


Figure 5 Snubber circuits

(a) C snubber, (b) RC snubber,

(c) Discharge RCD snubber, (d) Non-discharge RCD snubber



(a) Circuit of double pulse switching test

(b) Waveform of V_{DS}, I_D during turn off

Figure 9 turn-off surge comparison（with/without snubber）

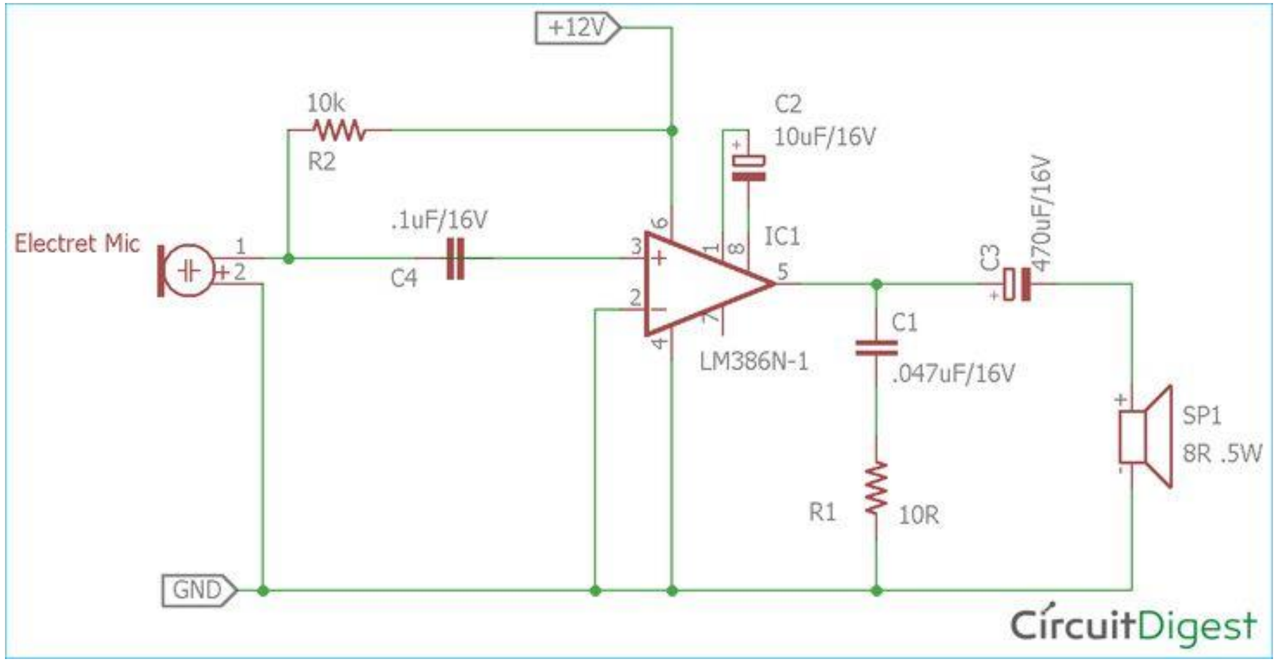
Courtesy: https://fscdn.rohm.com/en/products/databook/applinote/discrete/sic/mosfet/sic-mos_snubber_circuit_design_an-e.pdf

Flyback RC Snubber Design – Biricha Digital Power Ltd

Buck RC Snubber Design – Biricha Digital Power Ltd

https://www.youtube.com/watch?v=zzXnghQccCA

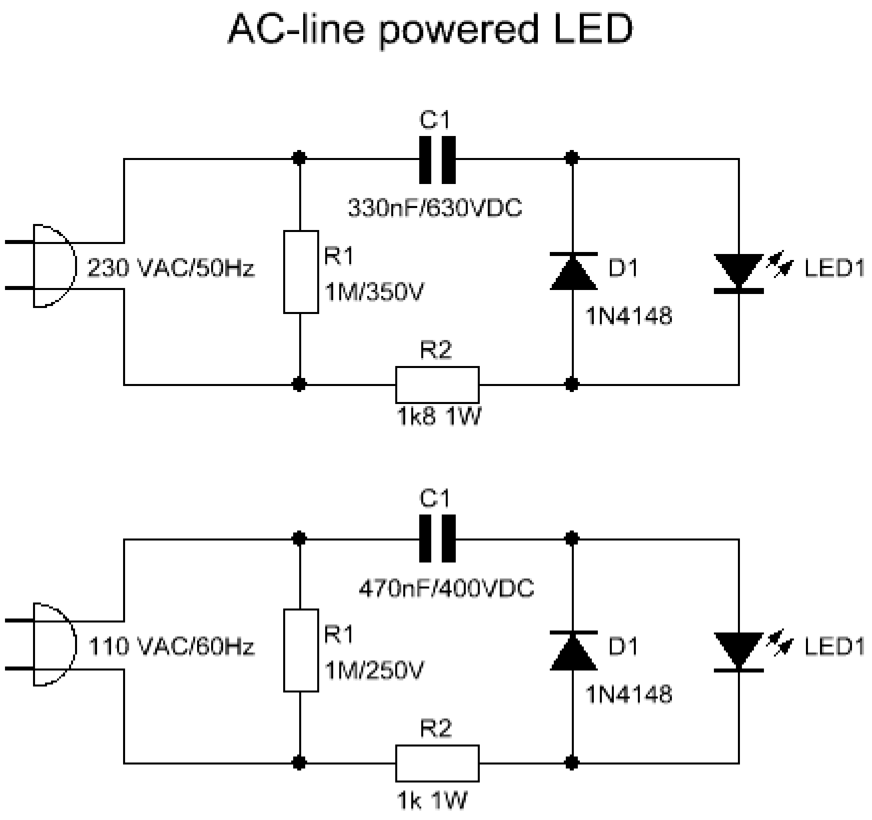
Example of a Coupling Capacitor application

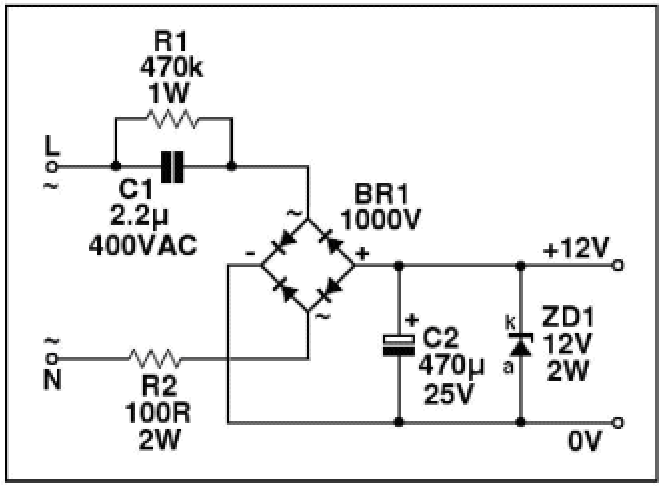


C4 allows coupling of only AC signal to the amplifier and blocks the DC bias given to the Electret Mic.

C3 allows only the AC signal to the speaker blocking DC voltages at output if any.

Capacitor as a lossless resistor for a simple power supply





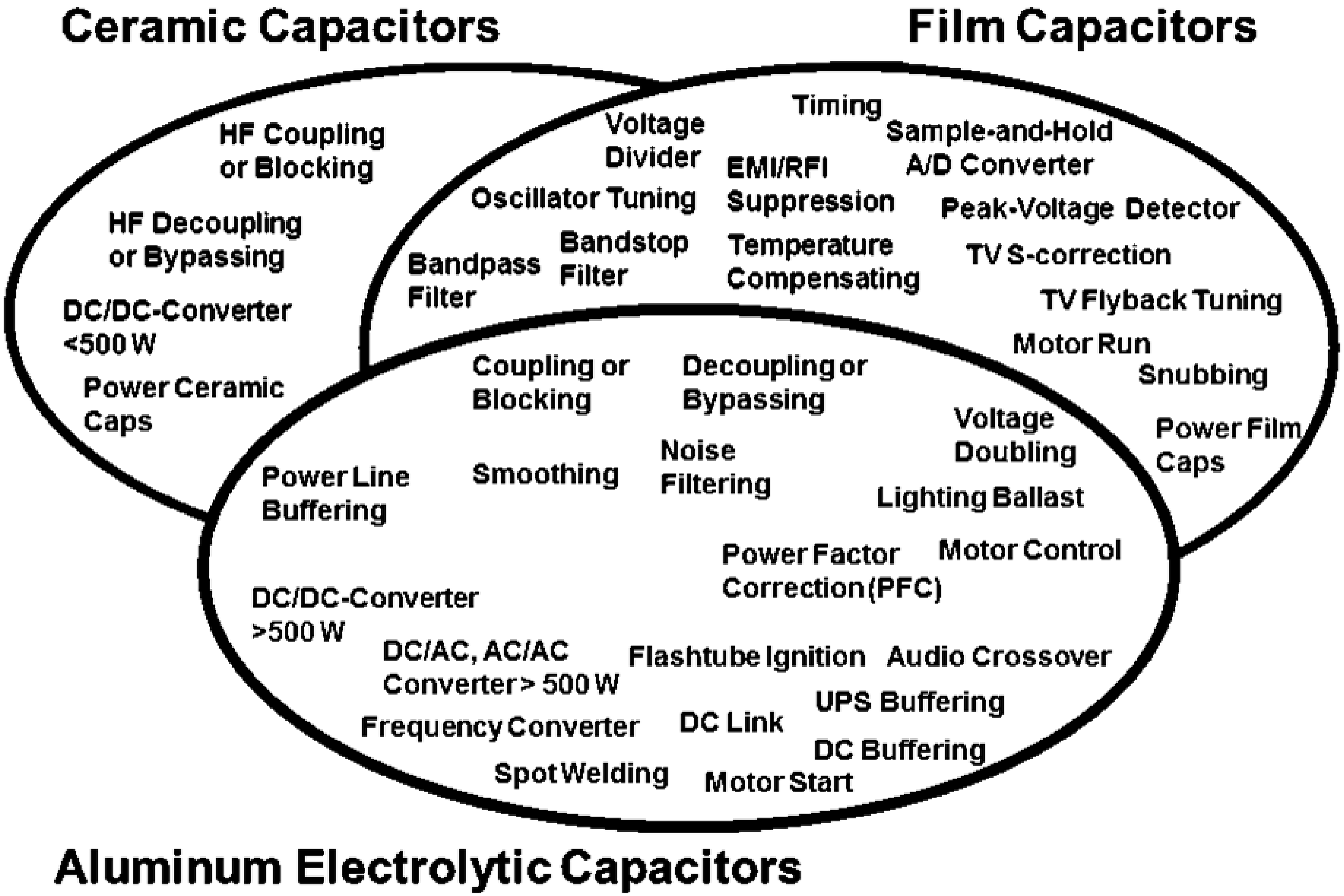
Where,

X_C = Inductive reactance in ohms

f = Frequency in hertz

C = Capacitance in farads

Popular capacitors and applications



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