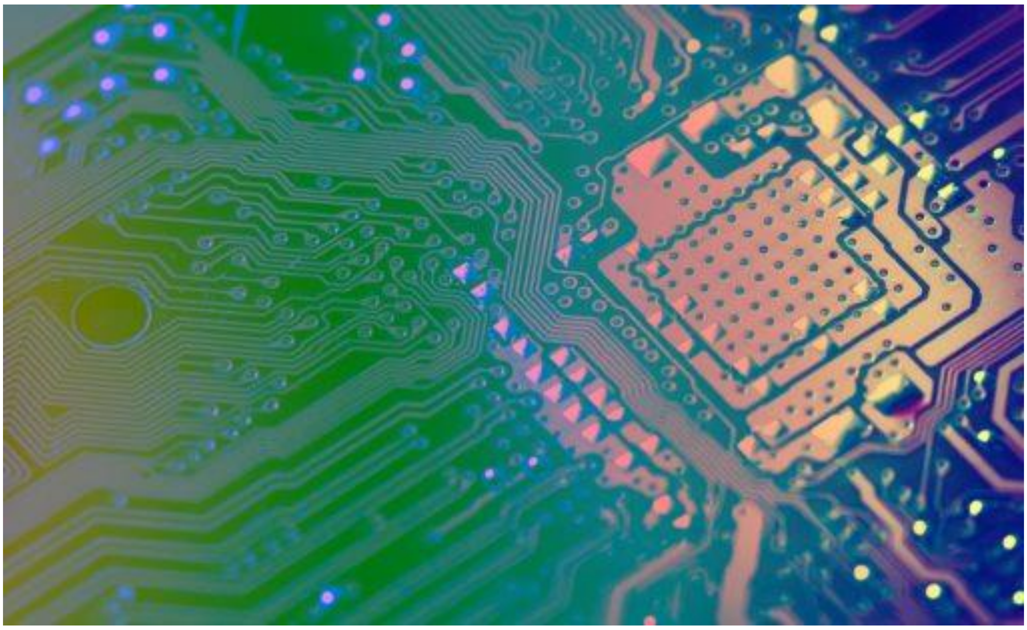
PDN BASICS



Source- Zuken

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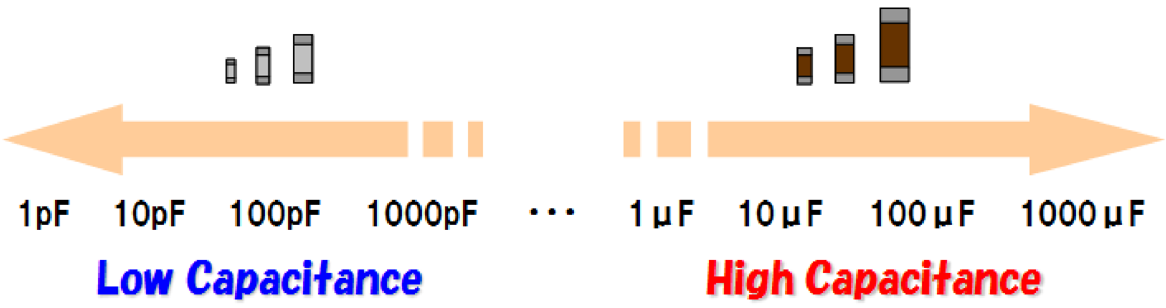
What is Capacitance of a Capacitor?

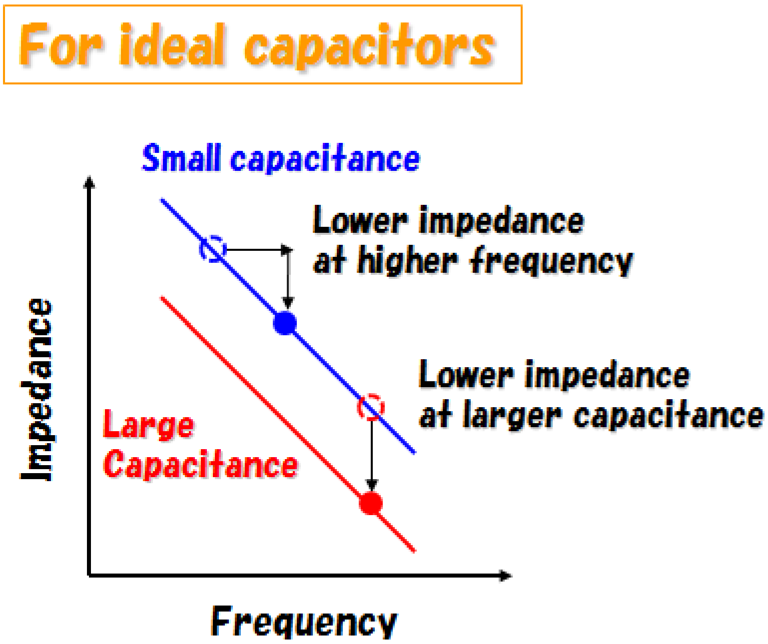
Capacitance is a physical quantity that describes the ability of electrical storage in capacitors. F(Farad) is a unit for expressing capacitance.

A quantity expressed by F is too large for capacitance range where ceramic capacitors are generally used. Instead, µF(micro Farad, one millionth of Farad) and pF(pico Farad, one trillionth of Farad) are often used as capacitance units of ceramic capacitors. We can roughly divide ceramic capacitors more than 1µF to high capacitance, and ones less than 1000pF to low capacitance category. However, the criteria of division depend on situations.



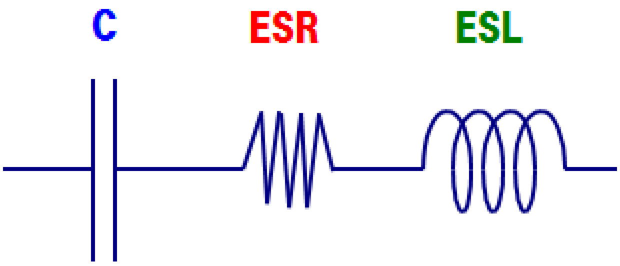
What are impedance frequency characteristics in capacitors?

Impedance of capacitors depends on capacitance and frequency. In an ideal capacitor, impedance becomes lower as capacitance is larger. Also, the impedance becomes lower as the frequency is higher.



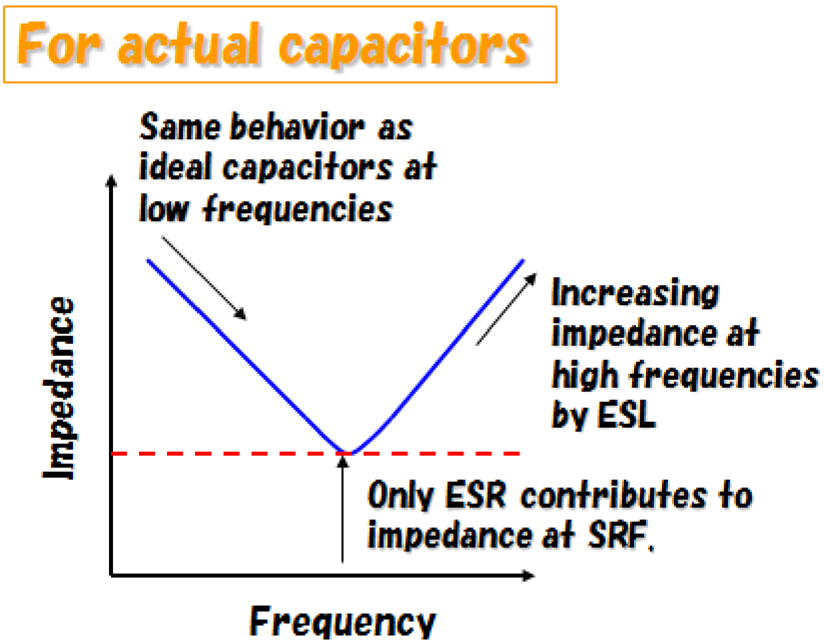
What is ESR/ESL of capacitors?

Actually, the capacitor has resistance and inductance. In a simple expression, those characteristics can be written as a R, L, C serial equivalent circuit model. This R is called Equivalent Series Resistance **(ESR)** and L is called Equivalent Series Inductance **(ESL)**



Serial Equivalent Circuit Model for capacitors

Different from an ideal capacitor, the impedance of actual capcitor changes its tendency at a certain frequency because of ESL. This frequency is called Self Resonant Frequency **(SRF)**. In higher frequency range than SRF, the impedance becomes larger by increasing frequency because ESL affects to impedance. At SRF, capacitance and ESL mutually erase each impedance. Therefore, only impedance by ESR remains at SRF.



Thus, the impedance of capacitor depends on frequency. That is impedance frequency characteristics in capacitors.

ESR and ESL both cause reduction of performance. Generally speaking capacitors with lower ESR and ESL work better than higher ones. If ESR of a capacitor is large, it may cause generation of heat and voltage drop when the IC is operating. If ESL of a capacitor is large, it may cause ringing of waveform. ESR and ESL also varies depending on frequency in actual capacitors. Therefore, it is important to know ESR and ESL value at frequency in our concern. Multilayer ceramic capacitors are generally superior in ESR and ESL characteristics to other kind of capacitors. There are Decoupling Capacitors that have even more lower ESR and ESL than general ceramic capacitors.

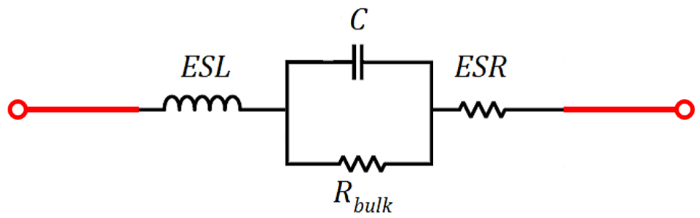
Typical ESR values

	10V	16V	25V	35V	63V	160V	250V	400V	630V
4.7µF	42.0Ω	35.0Ω	29.0Ω	24.0Ω	20.0Ω	16.0Ω	13.0Ω	11.0Ω	8.5Ω
10µF	20.0Ω	16.0Ω	14.0Ω	11.0Ω	9.3Ω	7.7Ω	6.3Ω	5.3Ω	4.0Ω
22µF	9.0Ω	7.5Ω	6.2Ω	5.1Ω	4.2Ω	3.5Ω	2.9Ω	2.4Ω	1.8Ω
47µF	4.2Ω	3.5Ω	2.9Ω	2.4Ω	2.0Ω	1.60Ω	1.30Ω	1.10Ω	0.85Ω
100µF	2.0Ω	1.60Ω	1.40Ω	1.10Ω	0.93Ω	0.77Ω	0.63Ω	0.53Ω	0.40Ω
220µF	0.90Ω	0.75Ω	0.62Ω	0.51Ω	0.42Ω	0.35Ω	0.29Ω	0.24Ω	0.18Ω
470µF	0.42Ω	0.35Ω	0.29Ω	0.24Ω	0.20Ω	0.16Ω	0.13Ω	0.11Ω	0.09Ω
1000µF	0.20Ω	0.16Ω	0.14Ω	0.11Ω	0.09Ω	0.08Ω	0.06Ω	0.05Ω	0.04Ω
2200µF	0.09Ω	0.08Ω	0.06Ω	0.05Ω	0.04Ω	0.04Ω	0.03Ω	0.02Ω	0.02Ω
4700µF	0.04Ω	0.04Ω	0.03Ω	0.02Ω	0.02Ω	0.02Ω	0.01Ω	0.01Ω	0.01Ω
10000µF	0.02Ω	0.02Ω	0.01Ω	0.01Ω	0.01Ω	0.01Ω	0.01Ω	0.01Ω	0.00Ω
22000µF	0.01Ω	0.01Ω	0.01Ω	0.01Ω	0.00Ω	0.00Ω	0.00Ω	0.00Ω	0.00Ω

Remember, lower ESR is better.

Capacitor Circuit Model with ESL

In a capacitor, equivalent series inductance (ESL) is the apparent inductance in a capacitor, which only becomes noticeable beyond certain frequencies. There is also some equivalent series resistance (ESR). Finally, there is some leakage or bulk resistance in the capacitor, which exists in parallel with the ideal capacitance, ESL, and ESR. This is shown in the following image, as well as the true capacitor impedance.



Impedance: $Z = \left(\frac{i\omega C}{1-\omega^2 C\cdot ESL + i\omega C\cdot ESR} + \frac{1}{R_{bulk}}\right)^{-1} \approx \frac{1-\omega^2 C\cdot ESL + i\omega C\cdot ESR}{i\omega C}$

Self-resonance: $\omega_r = \frac{1}{\sqrt{C\cdot ESL}}$

Because the dielectric material in the capacitor is strongly insulating, the value of Rbulk is normally very large (~100 GOhms), so it can be ignored when calculating the capacitor's impedance. Therefore, we need to focus on the ESL and ESR values when selecting capacitors.

Self-Resonance and ESL

If we look at the above circuit model, we will see that a real capacitor is an RLC circuit, so it has some self-resonant frequency as defined above. Similar RLC models are used to describe the real behaviour of inductors, transformers, and even semiconductors like diodes and transistors. This self-resonant frequency is the reason why real capacitors can act like inductors; when the driving frequency is larger than the self-resonant frequency, the inductive behaviour of the component dominates.

Why do we need to have Low ESL and ESR?

In general, we can never have a capacitor with zero ESL and ESR, but some applications demand very low values.

There are three reasons we want low ESL values when selecting a capacitor, particularly for high speed/high-frequency applications:

- **In filtering applications**: Low ESL means the self-resonant frequency is higher, so the capacitor behaves like an ideal component over broader frequencies.
- **In power applications:** the transient response will be faster, meaning the capacitor can discharge and deliver power faster. The same benefits for filtering also apply in power applications. Low ESR is also important here as charging/discharging is faster when ESR is lower.
- **In decoupling applications:** When used for decoupling/bypassing on high-speed ICs, low-ESL capacitors provide a greater reduction in ground bounce and supply bounce.

The image below shows how ESL affects the impedance of a theoretical 10 nF capacitor with 0.01 Ohms ESR. The various curves show impedance profiles for different ESL values (1 nH, 10 nH, and 100 nH). From the graph, we see that the impedance is capacitive up to the self-resonant frequency, regardless of the ESL value and then becomes inductive beyond the self-resonant frequency.

We see that the impedance for capacitors used in applications like switching power supplies, inverters, or power converters, ESL is generally not such a major problem. PWM driver signals are generally slow enough that most of the power is concentrated below the self-resonant frequency, so almost any capacitor with high voltage rating could be used. The exception is when we opt for a much higher switching frequency (MHz and higher) and faster rise time (~1 ns) to ensure very efficient power conversion. In that case, our PWM driver might excite a self-resonance, and low-ESL capacitors are needed.

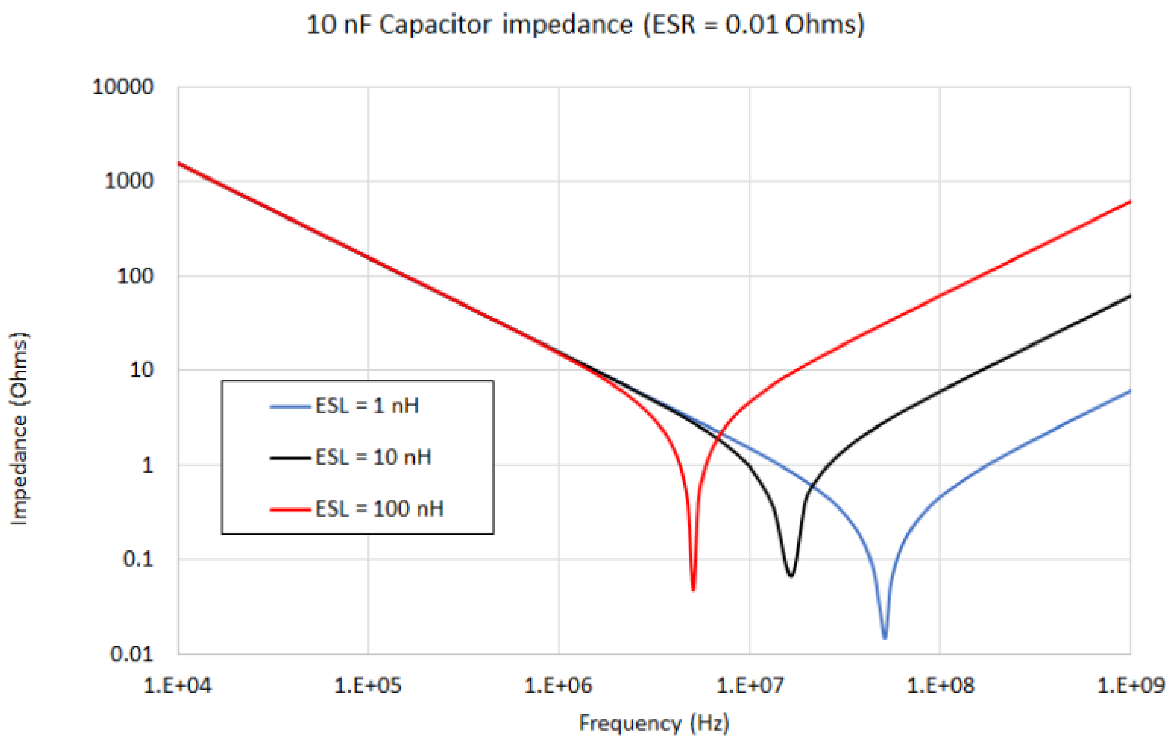


Image source - Octapart

For digital decoupling applications, where we need to ensure current drawn into a PCB's PDN is smooth, using low ESL capacitors helps ensure the PDN impedance is smooth out to higher frequency. The goal is to keep PDN impedance below some target value as a low impedance translates into a small voltage disturbance on the PDN. This is why outdated high speed design application notes will tell we to use three capacitors for decoupling each IC (10 nF, 1 nF, and 100 pF). For advanced components like high speed FPGAs, which can have very low rise times, the decoupling strategy can be much more complex as we need flat impedance out to 10's or 100's of GHz.

What Determines Capacitor ESL and ESR?

There are three factors that contribute to the ESL and ESR values of a capacitor. These include:

- **Dielectric material:** The contact resistance between the dielectric and the capacitor lead determines the ESR value, and the permeability of the dielectric determines the ESR value.
- **Package size:** This factor has the greatest effect on ESL and ESR in a capacitor. Larger packages will have larger leads and contacts against the dielectric, so they can have larger ESL values.
- **Mounting style:** Through-hole components tend to have higher ESL than SMD capacitors due to the large size of the leads on through-hole capacitors.

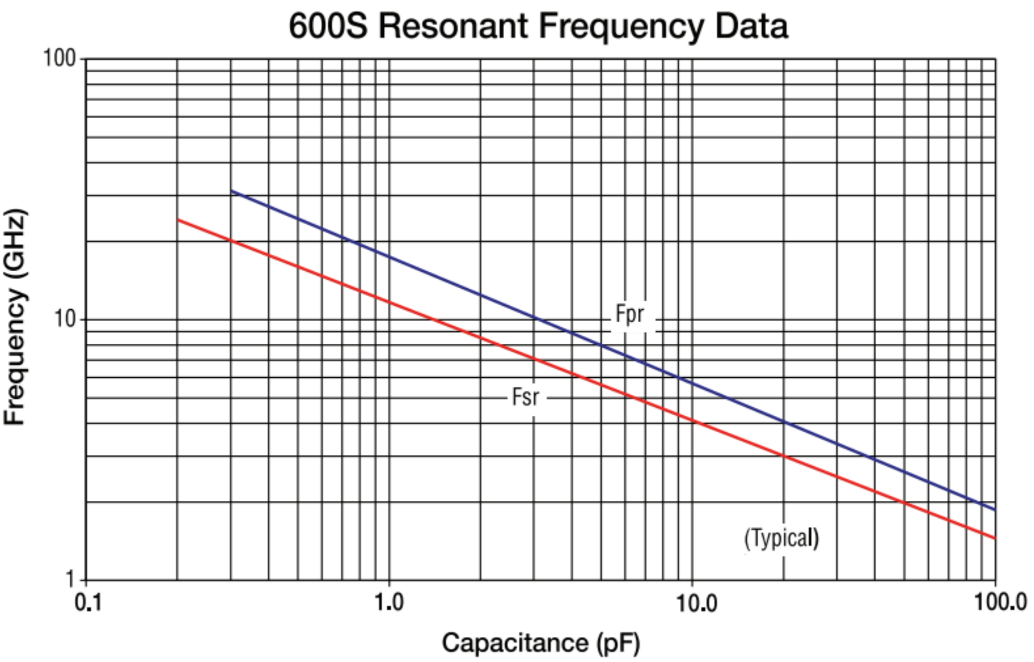
Because the dielectric material used in the capacitor determines ESL and ESR, we can now see why some IC datasheets and application notes will recommend a specific type of capacitor. Certain types of capacitors (e.g., tantalum, ceramic, etc.) may tend to have lower self-resonant frequencies, so they are a better choice for use in high-speed digital applications. Meanwhile, for power electronics, the use of larger capacitors is more about ensuring a high voltage rating and maintaining stable DC output, so ESL and self-resonance are less important.

Selecting a Low-ESL Capacitor

Unfortunately, when we need to find a low-ESL capacitor, most datasheets do a poor job of giving we a specific value for ESL. Datasheets might do a better job showing an ESR value, which is important for understanding how flat the impedance curve is. Some datasheets for capacitors that are specifically marketed as high-frequency capacitors may include an impedance vs. frequency curve, which does help we immediately determine if the capacitor will meet our bandwidth requirements.

Identify a Candidate Low-ESL Capacitor

Because the ESL values of capacitors are rarely found in datasheets, we will need to look at product guides from the manufacturer. If we can find a chart like that shown below, we can get a good idea of the ESL value for our capacitor. The following chart shows how self-resonance and capacitance are related for the American Technical Ceramics 600 Series of MLCCs, and the slope of the curve is related to the ESL value of the capacitor.



ATC 600 Series Data Sheet Test Condition Description

Capacitors horizontally mounted on 13.3-mil thick Rogers RO4350® softboard, 29-mil wide, 1/2 oz. Cu traces.
FSR = lowest frequency at which S11 response, referenced at capacitor edge, crosses real axis on Smith Chart.
FPR = lowest frequency at which there is a notch in S21 magnitude response.

Image source - Octapart

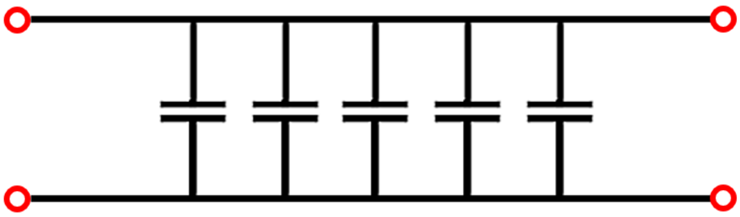
Digital vs. Analog

Selecting a low-ESL capacitor for an analog system, such as a wireless system, is rather easy. Simply check that the capacitor acts like an ideal capacitor and that its self-resonant frequency is larger than the operating frequency in the system. Because digital signals are broadband, we need to compare the entire impedance vs. frequency curve to our signal bandwidth, we can't just look at a single frequency.

Decoupling with Low-ESL Capacitors

Remember, physically smaller capacitors have lower ESL values and thus higher self-resonant frequency; this is another reason why physically smaller capacitors are recommended for high-speed digital systems. If we look at the layout and PDN decoupling scheme in a typical high-speed digital system, we will see there are multiple capacitors placed in parallel in the decoupling network. There is a specific reason for this: using multiples of the same capacitor in parallel will increase the total equivalent capacitance and decrease the PDN impedance, but it won't change the resonance frequency. This is shown in the example below for 5 capacitors with the same C and ESL values.

5 capacitors, each with same C and ESL



Equivalent impedance: $Z_{eq} = \frac{1-\omega^2 C\cdot ESL}{i5\omega C} \rightarrow \omega_r = \frac{1}{\sqrt{C\cdot ESL}}$

Image source - Octapart

We have ignored ESR in the above diagram, but we get the same result regardless; we will leave this as an exercise for the reader. The point here is, if we need to select a low-ESL capacitor with high self-resonance frequency, we can use a smaller capacitance, and just put multiple capacitors in parallel. The frequency response for a single low-ESL capacitor or multiple identical capacitors in parallel will be the same.

The same ideas do not strictly apply to different capacitors with different C or ESL values placed in parallel. In this case, there will be multiple resonance peaks due to interaction between different RLC networks with different poles, and a more thorough analysis is needed to understand the impedance and frequency response of these capacitor networks.

Functions of a Bypass (Decoupling) Capacitor

A bypass capacitor is a capacitor that shorts AC signals to ground, so that any AC noise that may be present on a DC signal is removed, producing a much cleaner and pure DC signal.

A bypass capacitor essentially bypasses AC noise that may be on a DC signal, filtering out the AC, so that a clean, pure DC signal goes through without any AC ripple.

When we look at the purpose they are used for, there is not much difference between the two types of capacitors. Surprisingly, most of the times the decoupling capacitors are also called as the Bypass capacitors. This is because they are shunted to the ground sometimes.

The below figure explains the complete functionality of a bypass (decoupling) capacitor.

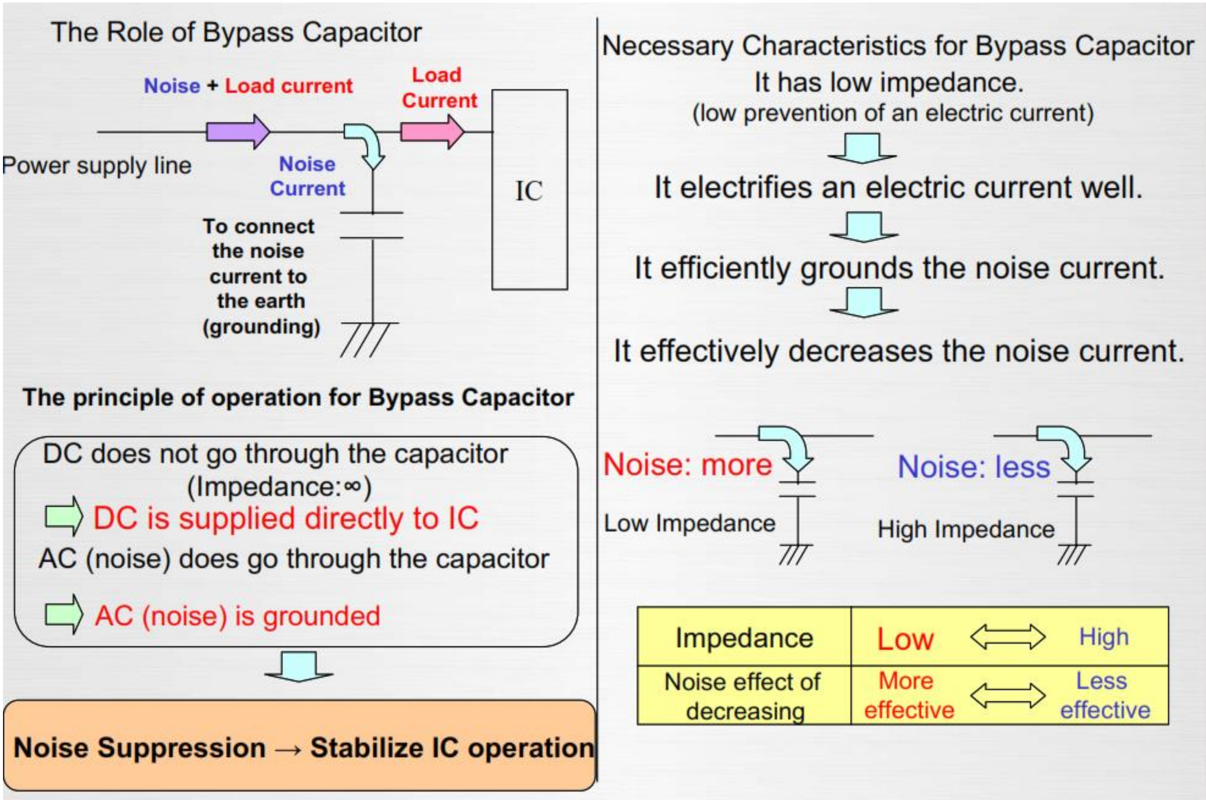


Image source - Yuden

References

https://www.yuden.co.jp/

https://octopart.com/