TECHNICAL PAPER

The Application of Capacitors in Power Supply Regulator Circuits

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Abstract
Advancements in electronic technology over the last decade have led to smarter consumer electronics. As devices become smarter, the components used to power them are shrinking, resulting in small, but incredibly powerful devices — ones small enough to fit inside a pocket or around a wrist. With these smaller, denser designs, it can be impossible to separate analog and digital domains in the layout, as best practices used to dictate years ago. Today, design engineers are compelled to use many capacitors in the power network to attenuate high-frequency digital noise. Circuits are designed to expect pure, clean power without noise that will impact analog circuits.

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ADVANCED CONSUMER ELECTRONIC DEVICES

Advancements in electronic technology over the last decade have led to smarter consumer electronics. As devices become smarter, the components used to power them are shrinking, resulting in small, but incredibly powerful devices — ones small enough to fit inside a pocket or around a wrist. With these smaller, denser designs, it can be impossible to separate analog and digital domains in the layout, as best practices used to dictate years ago. Today, design engineers are compelled to use many capacitors in the power network to attenuate high-frequency digital noise. Circuits are designed to expect pure, clean power without noise that will impact analog circuits.

CAPACITORS IN POWER SUPPLY REGULATOR CIRCUITS

In a voltage regulator, capacitors are placed at the input and output terminals, between those pins and ground (GND). These capacitors' primary functions are to filter out AC noise, suppress rapid voltage changes, and improve feedback loop characteristics. They are also used as bulk energy storage, providing instantaneous current to either the input or the load, as needed by design. Capacitors are critical components to all voltage regulator circuits.

FUNDAMENTAL PARAMETERS OF CAPACITORS

The dielectric material, and the physical design structure, used to manufacture different types of capacitors, give them different characteristics. Before describing the characteristics of capacitors, we should first review some of their key parameters.

Resistance: The symbol R refers to the capacitor's DC resistance, described by the ratio of DC voltage to current through the conductor.

Reactance: The symbol X is the impedance part caused by inductance and capacitance in the AC circuit, including inductive reactance (XL) and capacitive reactance (XC).

Impedance: The symbol Z is a composite parameter. The real part is resistance, and the imaginary part is reactance. Total impedance can be expressed as: $Z = R + jX$.

Conductance: The symbol G refers to the ratio of the direct current to the voltage through the conductor. Conductance is the reciprocal of the resistance.

Susceptance: Symbol B is the imaginary part of admittance, including capacitive (BC) and inductive (BL) components.

Admittance: The symbol Y is the reciprocal of the impedance Z, and therefore also a composite parameter. The real part is the conductance, while the imaginary part is the susceptance. Admittance can also be expressed as: $Y = G + jB$

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FUNDAMENTAL PARAMETERS OF CAPACITORS CONTINUED

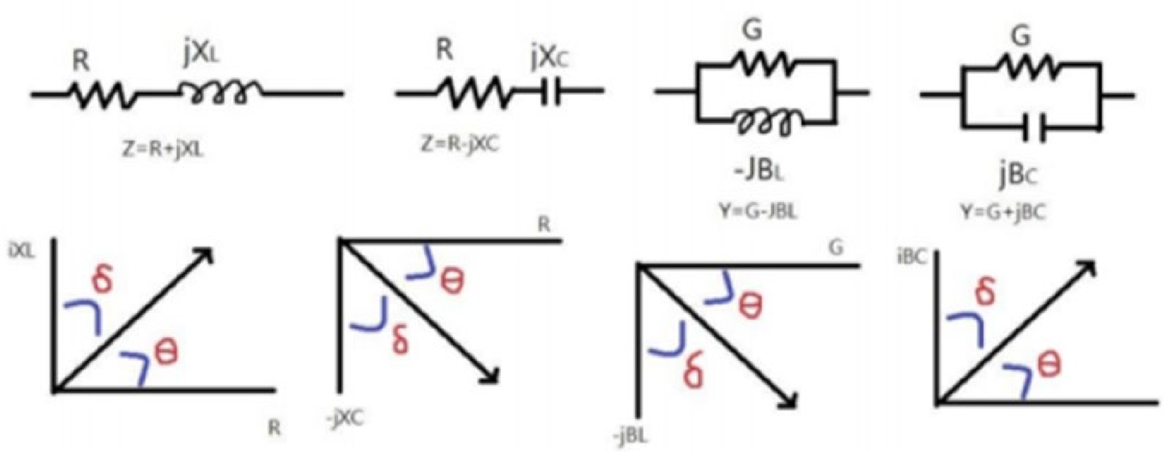

Figure 1: Representation of impedance and admittance

Figure 1 shows that when elements are connected in series, a positive θ indicates a more inductive component, while a negative θ indicates a more capacitive component. At exactly θ = +90°, the impedance would be entirely imaginary, and it would indicate a pure inductive element. At exactly θ = -90°, the impedance would again be entirely imaginary, indicating a pure capacitive element. If the elements were connected in parallel, these relationships would invert; θ = +90° would indicate a capacitive element, while θ = -90° would indicate an inductive element.

GENERAL CHARACTERISTICS OF COMMON CAPACITOR TYPES

The characteristics of several types of common capacitors are presented in the table below:

TYPE	ADVANTAGES	DISADVANTAGES
FILM	• High stability • Low-temperature coefficient • Large insulation resistance • Large Q	• Bigger size • Higher price • Poor characteristics while high temperature
CERAMIC	• Low ESR - High Ripple Rating • Good reliability • Non-polar • Wide capacitance and voltage range • Surge robust	• Cracking • Higher price for Hi-CV • Capacitance value decreases dramatically with DC/AC bias and temperature • Short circuit failure mode • Noise issue

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GENERAL CHARACTERISTICS OF COMMON CAPACITOR TYPES

The characteristics of several types of common capacitors are presented in the table below:

TYPE	ADVANTAGES	DISADVANTAGES
TANTALUM	• Unlimited lifetime • Lower profile (height) for height restrictive apps. • High Long-term reliability • Stable electrical parameters • Self-healing mechanism • Wide temperature range • Volumetric efficiency • No noise issues • Tantalum polymer technology up to 125V rated	• Higher price • Limited to lower voltage • Shorting failure mode • Derating rules • Severe failure mode
ALUMINUM	• Lower costs • Open circuit failure mode • High cap vs. voltage range in larger case sizes • Higher capacitance in large case sizes	• Limited life expectancy • Poor stability of impedance with low temperatures • Capacitance decreases with time • Lifetime decreases over high ripple current • Difficult to meet 3x Pb-free Reflow requirements • Low profile issue

ADVANCED CONSUMER ELECTRONIC DEVICES

There are no real, physical components that are purely resistive, capacitive, or inductive. All real passive components can be characterized as a combination of these ideal components, however. When a real-world resistor, capacitor, or inductor is represented as a combination of all three of these elements, that is called an equivalent circuit. An equivalent circuit diagram for an electrolytic capacitor is shown below:

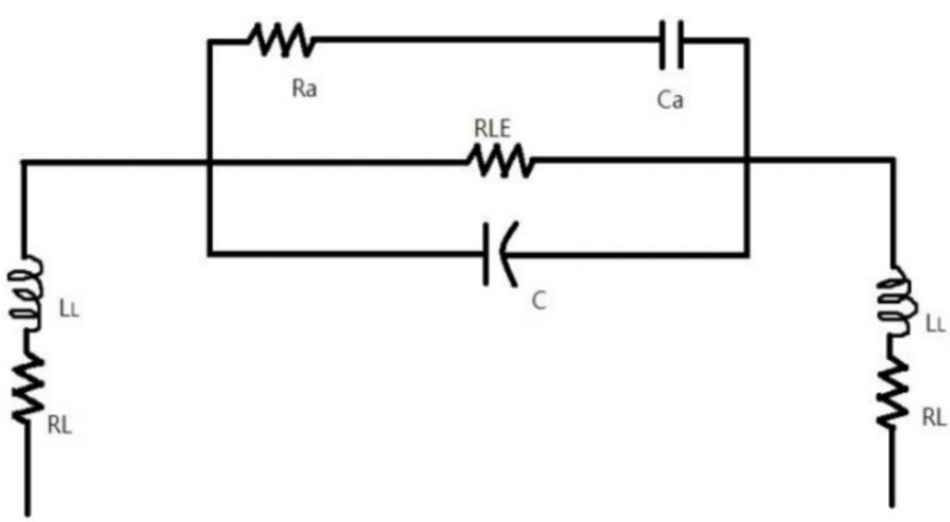

Figure 2: Equivalent circuit diagram for an electrolytic capacitor

ADVANCED CONSUMER ELECTRONIC DEVICES

In Figure 2, Ra and Ca are the resistance and capacitance caused by dielectric absorption. RLE is the resistance due to leakage current. RL and LL are the resistance and inductance introduced by the pin leads of the package.

In a multilayer ceramic capacitor, the equivalent circuit is slightly different because of its physical construction. There is a series resistance (ESR) and a series inductance(ESL) and a leakage resistance.

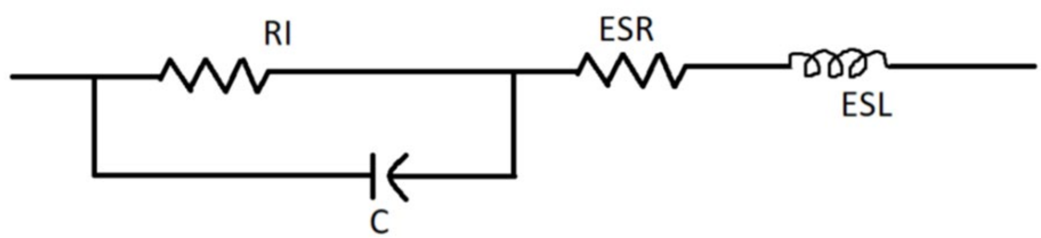

Figure 3: Equivalent circuit diagram for a multilayer ceramic capacitor

MEASURED CAPACITANCE CHARACTERISTICS

Given these general characteristics of capacitors, any specific capacitor device can be characterized by measuring a few key parameters. By measuring series resistance (RS), capacitance (CS), and inductance (LS), plus the magnitude (Z) and angle (*θ*) of the impedance vector, we can fully characterize a real capacitor.

Let's look at the AVX TCJ, a tantalum-polymer capacitor (TCJD106M050R0120E), as an example. The following data was gathered from a SPiCAT simulation:

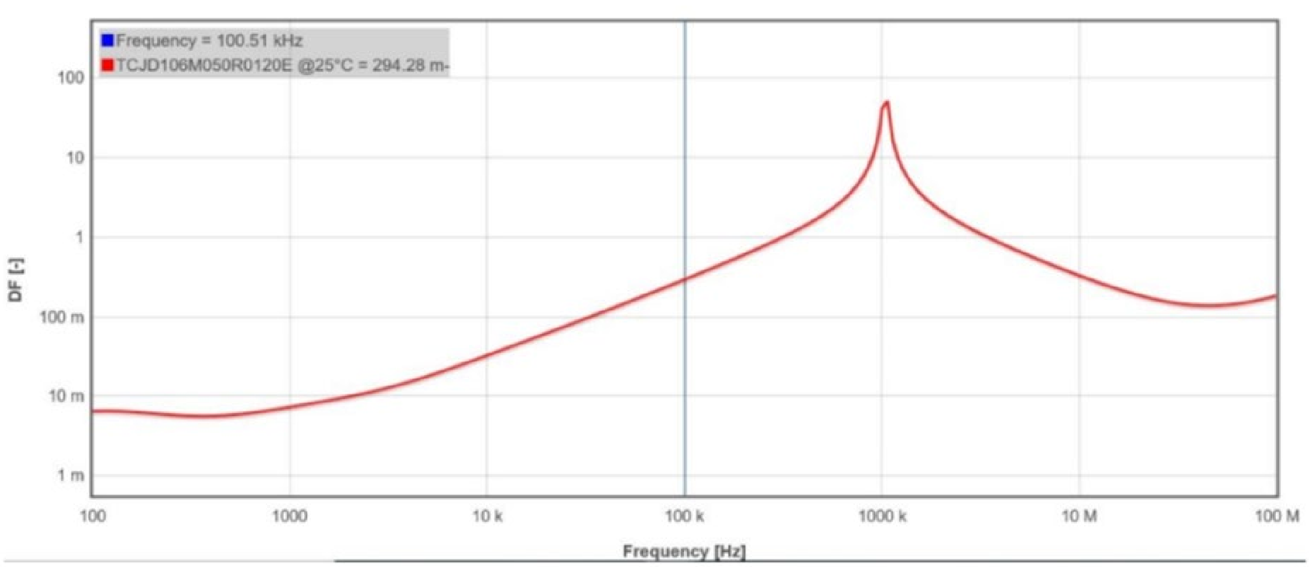

Figure 4A: AVX TCJD106M050R0120E (10uF / 50V) tantalum-polymer capacitor Spec data

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MEASURED CAPACITANCE CHARACTERISTICS CONTINUED

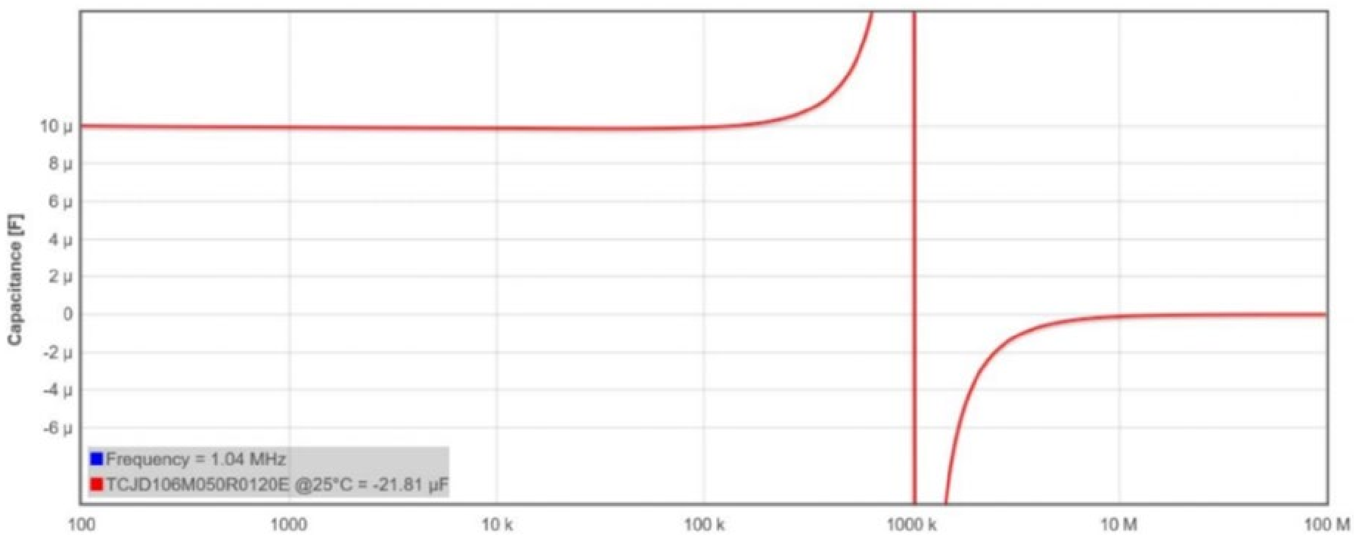
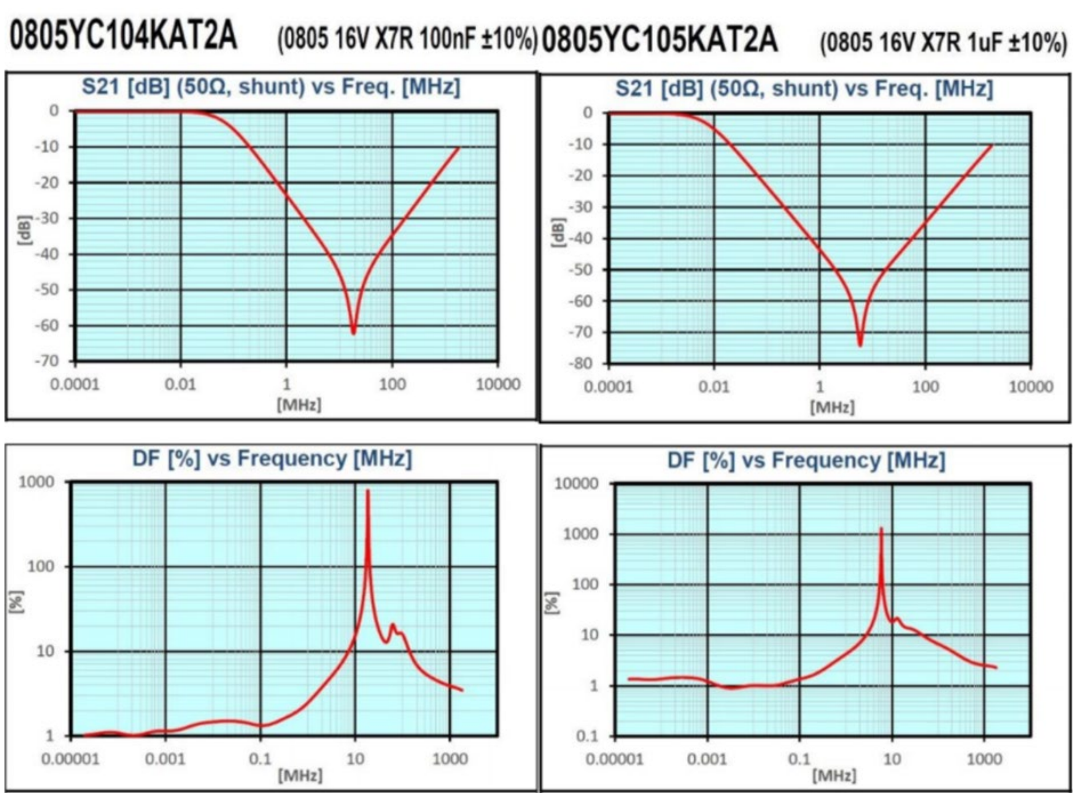


Figure 4B

Figure 4 shows that the 50V / 10uF Tan-polymer capacitor loses its capacitance when f> 1MHz, showing weak sensitivity. The tables below show the spec data of another two AVX MLCCs: 0805YC105KAT2A (16V / 1uF) & 0805YC104KAT2A (16V / 0.1uF). These two capacitors maintain a high Q value within a frequency of 1MHz, showing good capacitive characteristics.



MEASURED CAPACITANCE CHARACTERISTICS CONTINUED

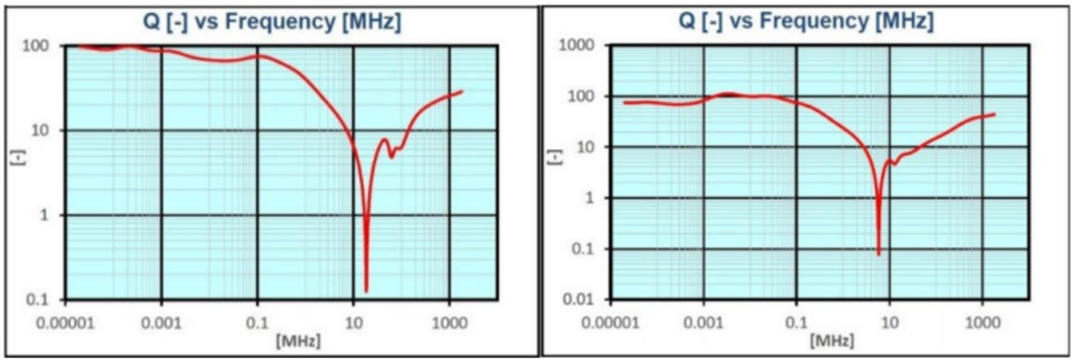


Figure 5: Data of two AVX MLCCs: 0805YC105KAT2A (16V / 1uF) & 0805YC104KAT2A (16V / 0.1uF)

THE EFFECT OF PARALLEL CAPACITANCE

So what effect does a typical filter capacitor circuit at an input or output have? Let's look at the common filter circuit shown below, where two capacitors are connected in parallel. One is a Tantalum polymer capacitor with a larger capacitance, and the other is a ceramic capacitor with a smaller capacitance, such as C1 = 10uF and C2 = 0.1uF.

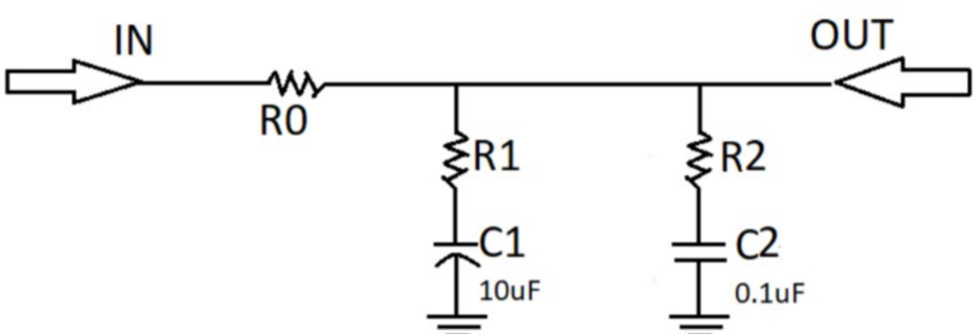


Figure 6: AC equivalent circuit with two capacitors in parallel

In the circuit shown in Figure 6, R0 represents the signal source's internal resistance, R1 is the equivalent series resistance of C1, and R2 is the equivalent series resistance of C2. Given this circuit, the transfer function can be represented as follows:

$$T(s) = \frac{Vout}{Vin} = \frac{\left(R1 + \frac{1}{C1 \bullet s}\right) // \left(R2 + \frac{1}{C2 \bullet s}\right)}{\left[\left(R1 + \frac{1}{C1 \bullet s}\right) // \left(R2 + \frac{1}{C2 \bullet s}\right)\right] + R0}$$

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THE EFFECT OF PARALLEL CAPACITANCE

This system, therefore, has two poles.

$$Z1 = \frac{1}{2\pi R1C1} \quad Z2 = \frac{1}{2\pi R2C2}$$

In a circuit like the one defined, where C1 >> C2, and R1 >> R2, the poles can be simplified as follows:

$$P1 = \frac{1}{2\pi(R0 + R1)C1} \quad P2 = \frac{1}{2\pi[(R0 // R1) + R2]C2}$$

Based on the above 50V / 10uF Tan-polymer capacitor and 16V / 0.1uF ceramic capacitor data, the following values can be given to the above components. ESR takes the value of f = 100kHz, R0 = 1Ω, C1 = 9.91uF, C2 = 0.0997uF (assumed), R1 = 120mΩ, R2 = 248.9mΩ,

As shown from the equations above, the first zero-point Z1 appears, which is formed by R1 and C1. If there were no capacitor C2, the AC curve would remain level with no more attenuation. It is because of the existence of C2 that the gain continues to decay after passing through the second pole P2 until the second zero-point Z2. Therefore, to make the gain of two capacitors in parallel more attenuated, Z2 can be shifted out; that is, the capacitors C2 and R2 are selected to be much smaller than C1 and R1.

This is the ideal curve calculated by MATHCAD assuming that the capacitances C and ESR are fixed values at all frequencies. In reality, according to the data presented above, C and ESR will vary with frequency, and ESL will appear at high frequencies.

Using the values suggested above, the poles and zeroes can be calculated as follows:

$$\frac{1}{2\ \pi \cdot 0.120\ \Omega \cdot 9.91\ \mu F} = \left(1.338 \cdot 10^{5}\right) \frac{1}{s}$$

$$\frac{1}{2\ \pi \cdot 0.2489\ \Omega \cdot 0.0997\ \mu F} = \left(6.414 \cdot 10^{6}\right) \frac{1}{s}$$

$$\frac{1}{2\ \pi \cdot \left(1\ \Omega + 0.12\ \Omega\right) \cdot 9.91\ \mu F} = \left(1.434 \cdot 10^{4}\right) \frac{1}{s}$$

$$\frac{1}{2\ \pi \cdot \left[\frac{1}{\left(\frac{1}{1\ \Omega + 0.12\ \Omega}\right)} + 0.2489\ \Omega\right] \cdot 0.0997\ \mu F} = \left[1.166 \cdot 10^{6}\right] \frac{1}{s}$$

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THE EFFECT OF PARALLEL CAPACITANCE

We then get the resulting curves:

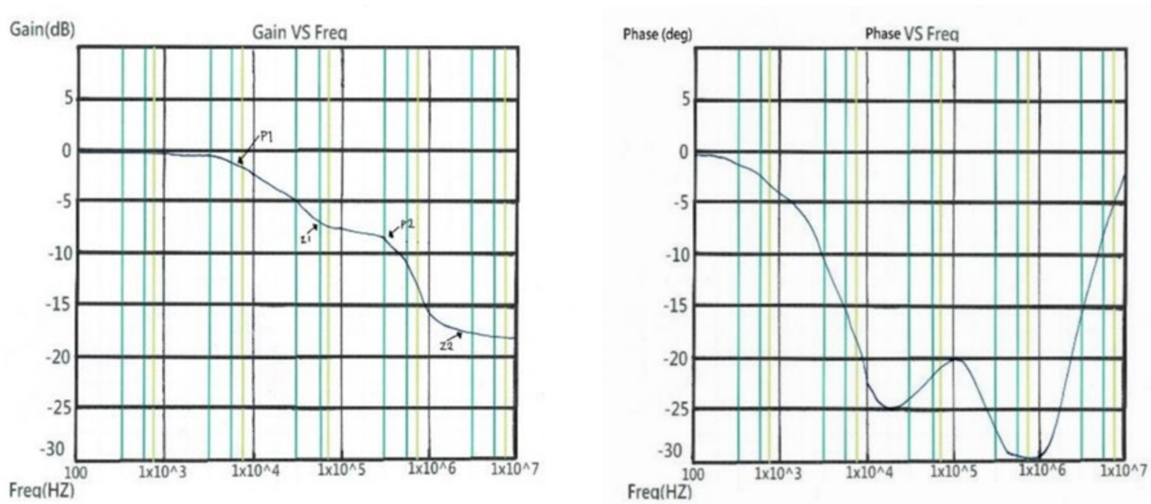


Figure 7: Amplitude / phase frequency characteristics of two capacitors in parallel.

If two identical capacitors are used — R1 x C1 = R2 x C2 — the system can be simplified into a one pole and one zero.

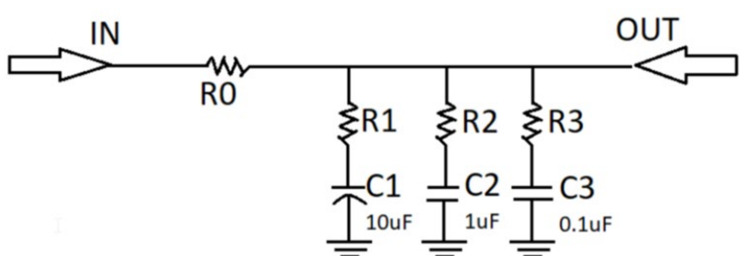
Zero point- >

$$Ze = \frac{1}{(R1 // R2) \bullet (C1 // C2) \bullet s} = \frac{1}{Re \bullet Ce \bullet s}$$

Pole point->

$$Pe = \frac{1}{[(R1 // R2) + R0] \bullet (C1 // C2) \bullet s} = \frac{1}{(Re + R0) \bullet Ce \bullet s}$$

It essentially becomes a single capacitor, with C = C1||C2, and R = R1||R2.
In the case where three capacitors are used in parallel, the transfer function can be expressed as follows:



$$T(s) = \frac{Vout}{Vin} = \frac{\left(R1 + \frac{1}{C1 \bullet s}\right) // \left(R2 + \frac{1}{C2 \bullet s}\right) // \left(R3 + \frac{1}{C3 \bullet s}\right)}{\left[\left(R1 + \frac{1}{C1 \bullet s}\right) // \left(R2 + \frac{1}{C2 \bullet s}\right) // \left(R3 + \frac{1}{C3 \bullet s}\right)\right] + R0}$$

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THE EFFECT OF PARALLEL CAPACITANCE

Assume that the above components have the values, R0 = 1Ω, C1 = 10uF, C2= 1uF, C3 = 0.1uF, R1 = 120mΩ, R2 = 50mΩ, and R3 = 240mΩ. We can then get the values of the three zeroes Z1, Z2 and Z3 as below:

$$\frac{1}{2\,\pi \cdot 0.12\;\Omega \cdot 10\;\mu F} = \left(1.326 \cdot 10^{5}\right)\frac{1}{s}$$

$$\frac{1}{2\,\pi \cdot 0.05\;\Omega \cdot 1\;\mu F} = \left(3.183 \cdot 10^{6}\right)\frac{1}{s}$$

$$\frac{1}{2\,\pi \cdot 0.24\;\Omega \cdot 0.1\;\mu F} = \left(6.631 \cdot 10^{6}\right)\frac{1}{s}$$

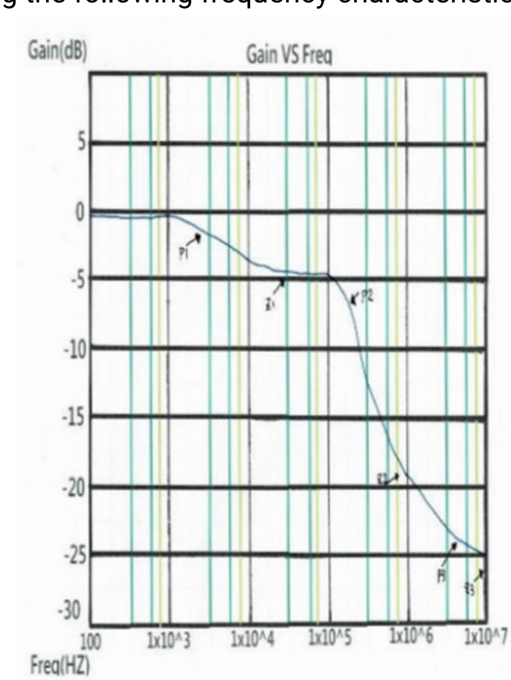
And the three poles:

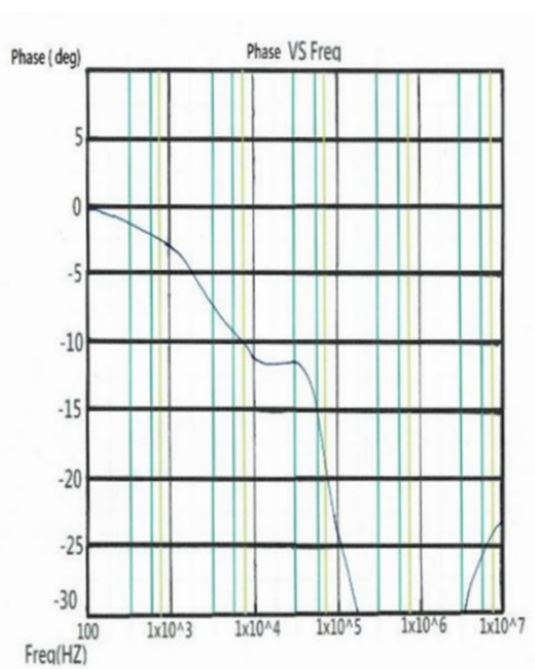
$$\frac{1}{2\,\pi \cdot \left(1\;\Omega + 0.12\;\Omega\right) \cdot 10\;\mu F} = \left(1.421 \cdot 10^{4}\right)\frac{1}{s}$$

$$\frac{1}{2\,\pi \cdot \left[\dfrac{1}{\left(\dfrac{1}{1\;\Omega + 0.12\;\Omega}\right)} + 0.05\;\Omega\right] \cdot 1\;\mu F} = \left[1.36 \cdot 10^{5}\right]\frac{1}{s}$$

$$\frac{1}{2\,\pi \cdot \left[\dfrac{1}{\left(\dfrac{1}{1\;\Omega + 0.12\;\Omega + 0.05\;\Omega}\right)} + 0.24\;\Omega\right] \cdot 0.1\;\mu F} = \left[1.129 \cdot 10^{6}\right]\frac{1}{s}$$

Yielding the following frequency characteristics curves:





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SELECTING THE RIGHT CAPACITOR

In order to achieve better noise attenuation when using multiple capacitors in parallel, capacitors with different capacitance (C) and equivalent series resistance (ESR) should be selected. This will cause the attenuation curve to start from the first pole and end at the last zero point. The capacitor with the largest capacitance determines the start frequency of attenuation, and the capacitor with the smallest capacitance determines the end frequency of attenuation. Reducing the pin length to minimize equivalent series inductance (ESL) is also crucial.

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