Power Device

Impedance Characteristics of Bypass Capacitor

There are various types of capacitors. If you select parts only based on their capacitance values, the requirements for bypass capacitors may not be satisfied, leading to malfunction of devices or nonconformity to standards. This application note focuses on the impedance characteristics of capacitors, and explains cautions for selecting bypass capacitors.

Role of bypass capacitor

A bypass capacitor on a power supply circuit plays roughly two roles. The first role is to release the noise component superimposed on the power supply line to the ground. Variations in voltage are mitigated by charging the capacitor if the noise component is higher or discharging if the noise component is lower than the steady state voltage. Furthermore, since the AC impedance of a capacitor is decreased with increase in frequency, the noise component with a higher frequency is released to the ground more easily. The second role is to suppress fluctuations in the power supply line due to a sudden change in the load current. Due to the presence of the wiring impedance on the power supply line, a sudden change in the load current generates a voltage drop. As a result, issues of problems related to deviation from the set voltage or voltage noise may occur. The bypass capacitor mitigates variations in voltage by discharging if the voltage is decreased or charging if the voltage is increased relative to the steady state voltage. This plays a role similar to an auxiliary power supply that functions for a short time.

Performance required for bypass capacitor

In both of these two roles, the capacitor charges when the voltage is increased above the steady state voltage, and discharges when the voltage is decreased below the steady state voltage. Therefore, the capacitor must be capable of responding to the noise frequency and the speed of the voltage variations.

Next, consider the performance required. Figure 1 shows a simplified equivalent circuit of a capacitor. C represents the electrostatic capacitance. ESR is an equivalent series resistance that represents the resistance components due to the type of dielectrics as well as the resistance components of electrodes and terminals. ESL is an equivalent series inductance that represents the inductance components generated due to structures of the capacitor, such as electrodes and terminals.

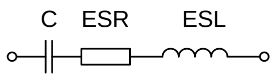

Figure 1. Simplified equivalent circuit of capacitor

The impedance of this equivalent circuit can be calculated with Equation (1), and its characteristics are shown in Figure 2. In the low frequency region, the impedance is determined by electrostatic capacity C. In the high frequency region, the impedance is determined by ESL. The self-resonance frequency is where C and ESL are series resonant and their impedances agree ($1/2\pi f C = 2\pi f ESL$). Since neither C nor ESL has influence, the impedance is determined only by ESR. The self-resonance frequency can be calculated with Equation (2). According to these characteristics, a capacitor must be used below its self-resonance frequency to function properly.

$$|Z| = \sqrt{ESR^2 + \left(2\pi f \times ESL - \frac{1}{2\pi f \times C}\right)^2} \quad [\Omega] \qquad (1)$$

$$f_r = \frac{1}{2\pi\sqrt{ESL \times C}} \quad [Hz] \qquad (2)$$

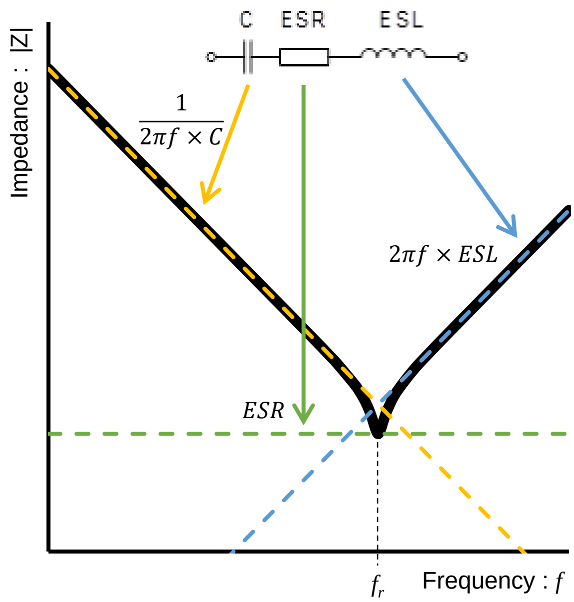

Figure 2. Impedance characteristics of equivalent circuit of capacitor

The following is a summary of key points in selecting the bypass capacitor.

1. Select a sufficiently large capacitance value so that the impedance is low at the noise frequency. The larger the capacitance value, the lower the impedance.
2. Use the capacitor in a region below its self-resonance frequency.
3. To reduce the impedance, select parts with a low ESR.
4. For high frequency noise, select parts with a low ESL.
5. Select a capacitance value that can store electric charges to suppress a voltage drop.

Impedance characteristics of ceramic capacitor

To keep the impedance of the power supply line low, a capacitor with a large capacitance, low ESR, and low ESL is required. However, it is impossible to cover a wide frequency bandwidth with a single type of capacitor. In general, a capacitor with larger capacitance has a larger size, leading to a higher ESL. Therefore, its self-resonance frequency decreases and the impedance increases in the high frequency region. On the other hand, a capacitor with smaller capacitance generally has a smaller size, leading to a lower ESL. Therefore, its self-resonance frequency is high and a low impedance is obtained in the high frequency region. However, due to the small capacitance value, the impedance increases in the low frequency region.

In some approaches, in order to decrease the impedance across a wide frequency bandwidth, multiple capacitors with different capacitance values for each different frequency bandwidth are connected in parallel. Figure 3 shows an example of multilayer ceramic capacitors (MLCCs). In this example, since the impedance increases above 1 MHz with one bypass capacitor of 22 μF, the noise is expected to worsen in the high frequency region (red line). By connecting capacitors from 100 pF to 1 μF in parallel, the combined impedance can be kept low (black line).

It should be considered that the impedance may be increased if MLCCs with widely different self-resonance frequencies are introduced due to a parallel resonance between their C and ESL. Check with the actual equipment. This parallel resonance is referred to as an anti-resonance point.

It should also be considered that the impedance characteristics of capacitors with the same capacitance can be different if their case sizes or model names are different. In addition, since an actual PCB has a parasitic inductance component due to wiring, the impedance value may not decrease according to the characteristics of the capacitor.

A guide for countermeasures against noise is provided by understanding the capacitance values that are effective in each frequency bandwidth from the graph in Figure 3. For example, improvement can be expected by connecting in parallel multiple MLCCs of 1 μF or 0.1 μF to reduce noise on the short wave (HF) band (such as short wave radio and citizens band radio), and multiple MLCCs of 0.01 μF as countermeasures for the ultrashort wave (VHF) band (such as FM radio).

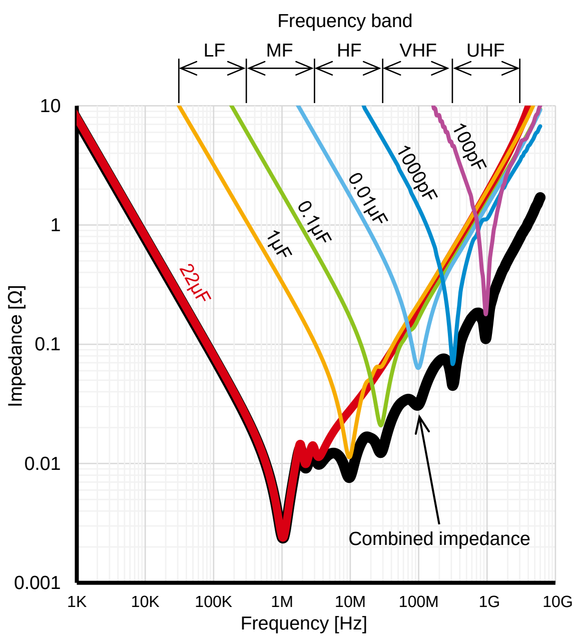

Figure 3. Example of impedance characteristics with multilayer ceramic capacitors of different capacitances connected in parallel. The impedance can be reduced across a wide bandwidth.

Impedance characteristics of electrolytic capacitor

Electrolytic capacitors may often be used because ceramic capacitors with large capacitance are expensive or unavailable. However, care must be taken since their impedance characteristics are higher compared with ceramic capacitors.

The red line in Figure 4 shows an example of the impedance characteristics of a 330 μF aluminum electrolytic capacitor. In this example, since the impedance is restricted by the ESR value above approximately 10 kHz, the impedance remains above the value. The lines from 100 pF to 22 μF represent the characteristics of MLCCs. By connecting these MLCCs with the aluminum electrolytic capacitor in parallel, the combined impedance can be kept low (black line).

The example in Figure 4 is intended to explain the effect of MLCCs and is not realistic as it has too many parts. However, the impedance can be kept low across a wide bandwidth, for example, by using a combination of about three capacitances as shown in Figure 5 and it is considered that a capacitor for the high frequency region is added as necessary.

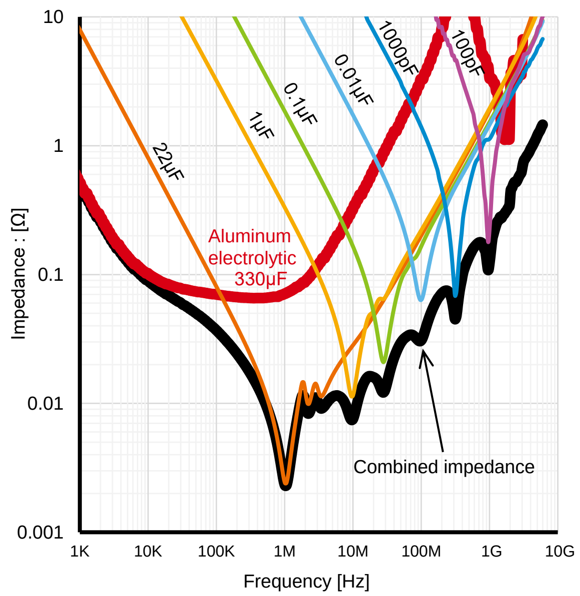

Figure 4. Example of impedance characteristics of aluminum electrolytic capacitor. The impedance can be reduced across a wide bandwidth by connecting multilayer ceramic capacitors of different capacitances in parallel.

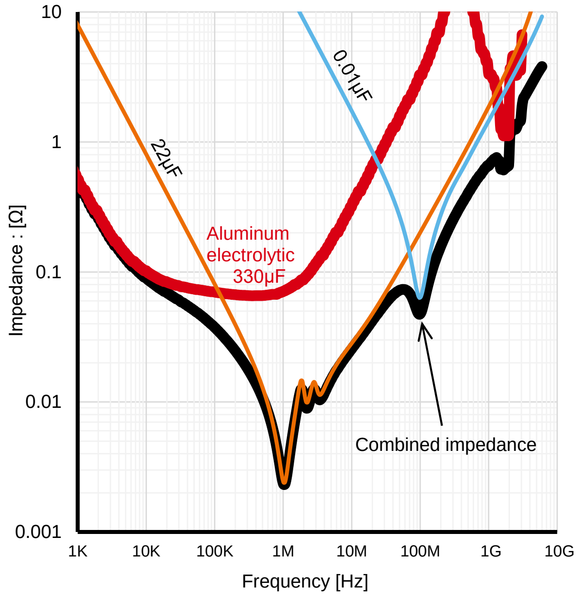

Figure 5. The impedance can be kept low across a wide bandwidth by a combination of about three capacitances, and it is considered that a capacitor for a high frequency region is added as necessary.

In addition, care must be also taken regarding the characteristics at a low temperature for electrolytic capacitors with wet electrolytes, including aluminum electrolytic capacitors. At a low temperature, electrolytic solutions used in electrolytic capacitors show increase in their viscosity and resistance as well as decrease in the ion mobility, causing decrease in the electrostatic capacitance and increase in ESR. As a result, the impedance at a low temperature is increased. Figure 6 shows an example of the impedance of an aluminum electrolytic capacitor. In this example, the impedance at -40°C is higher than the impedance at +25°C by an order of magnitude. If failure of circuit operation occurs, it is necessary to consider changing the aluminum electrolytic capacitor to a capacitor that can provide a low impedance even at a low temperature, such as a conductive polymer aluminum solid capacitor or conductive polymer hybrid aluminum electrolytic capacitor using a solid electrolyte. Figures 7 and 8 show an example of their impedance characteristics.

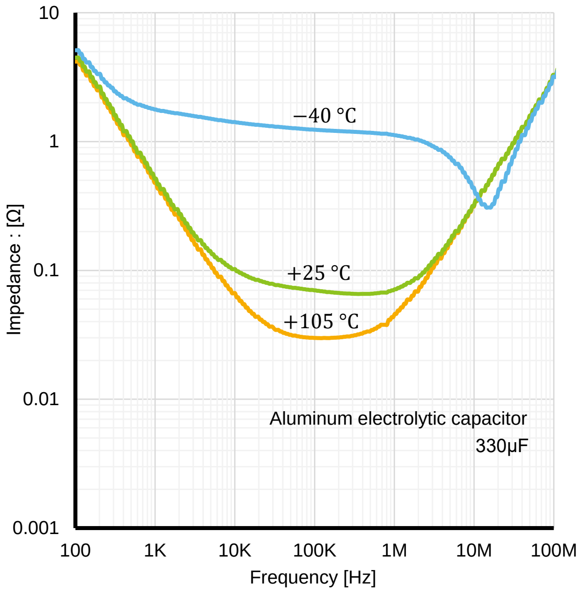

Figure 6. Example of impedance characteristics of aluminum electrolytic capacitor. Care must be taken with respect to decrease in the electrostatic capacitance and increase in ESR at a low temperature.

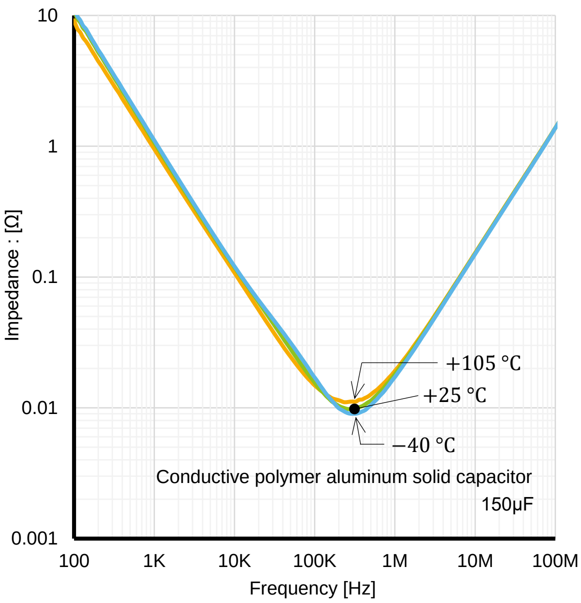

Figure 7. Example of impedance characteristics of conductive polymer aluminum solid capacitor

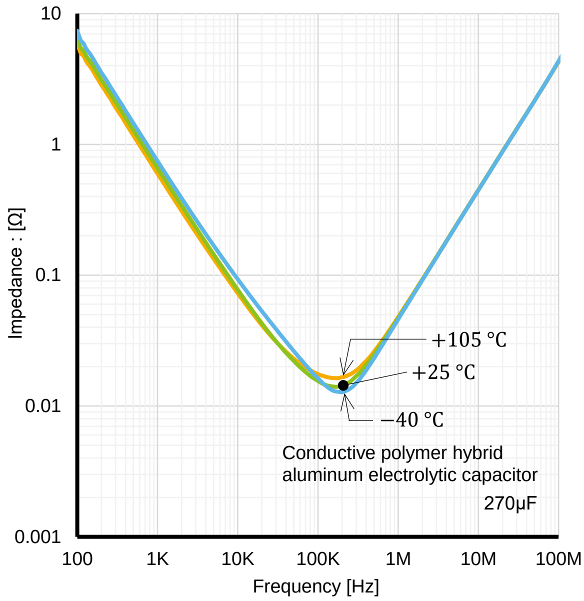

Figure 8. Example of impedance characteristics of conductive polymer hybrid aluminum electrolytic capacitor

Cautions for selecting alternative parts

After mass production of a product, alternative parts may be explored if existing parts are unavailable or cost reduction is pursued. However, if a third party unfamiliar with the circuit operation selects alternative parts by focusing only on the electrostatic capacitance and the voltage rating, problems, such as a malfunction or nonconformity to the EMC standards, may occur. This is caused by difference in shapes, structures, and materials among parts. Parts from the same manufacturer may have different characteristics if their model names are different only by a single character. Always check the impedance characteristics of the capacitors. Furthermore, this issue can be avoided by adding special notes to the circuit diagrams and BOMs of such important parts.

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