TECHNICAL PAPER

Key Parameters for Designing Ceramic Capacitors in SMPS Circuits

Kevin Cho

KYOCERA AVX Components Corporation
One AVX Boulevard
Fountain Inn, S.C. 29644 USA

Abstract

Capacitors are ubiquitous and indispensable components of electronic circuits used for a plethora of uses. For engineers looking to design multilayer ceramic capacitors (MLCCs) in switch-mode power supplies (SMPS) such as Buck and Boost converters, some essential parameters to be considered include the ripple current capability, ripple voltage, and power dissipation. Using the KYOCERA AVX SpiCalci10 model simulation tool for SMPS capacitors, this whitepaper will outline various MLCC characteristics, AC current capability, and other considerations for circuit design.

KEY PARAMETERS FOR DESIGNING CERAMIC CAPACITORS IN SMPS CIRCUITS

THE NEED FOR CAPACITORS IN ELECTRONIC CIRCUITS

Capacitors are critical elements in analog and digital electronic circuits utilized in many applications, including energy storage, coupling and decoupling, electrical noise suppression, bypassing, and more. Different applications have different performance requirements for capacitors with specific characteristics. The size and its materials of construction can be altered to enhance its properties, including:

- Capacitance
- Voltage
- Current
- Operational frequency range
- ESR
- ESL
- Temperature range
- Dielectric absorption
- Polarity
- Mechanical flexibility

DC-DC POWER CONVERSION IN SWITCHED MODE POWER SUPPLIES

Figure 1 shows how capacitors are used in voltage regulators:

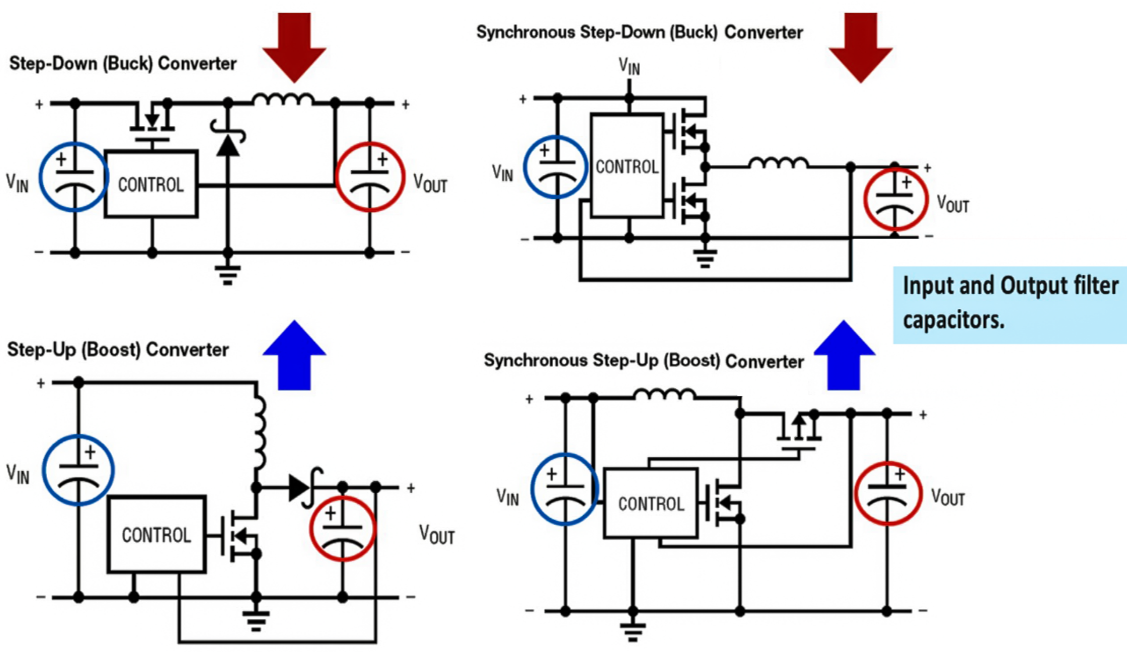


Figure 1: Capacitor application in Buck and Boost converters

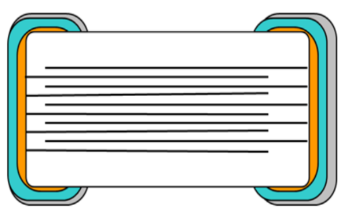
WHAT ARE MLCCS?

Multilayer ceramic capacitors, also known as MLCCs, are the capacitors of choice in applications requiring small capacitances and are constructed using alternating layers of ceramic and metal. MLCCs are suitable for modern high-frequency applications due to their ultra-low equivalent series resistance (ESR). MLCCs can be broadly classified into two types:

Class 1: NPO/COG materials (Temperature compensation MLCC)
Class 2: X7R, X5R, X7S, X6S,Y5V materials (High dielectric constant MLCC)

The main difference between the two is that the capacitance of Class 2 varies with changes in the measurement voltage and temperature, while there is no capacitance variation in Class 1.

Figures 2-4 and Table 1 show some of the most important characteristics of MLCCs:



$$C = \frac{\text{Number of Layers} * K * \text{Active Area}}{\text{Dielectric Thickness}}$$

Figure 2: MLCC construction. Alternate layers of electrodes and dielectric materials effectively create multiple parallel capacitors in a single device to increase the capacitance.

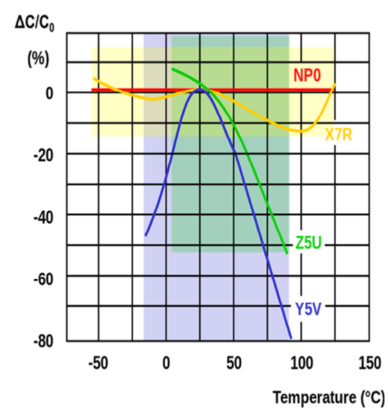


Figure 3: Temperature coefficient of capacitance (TCC)

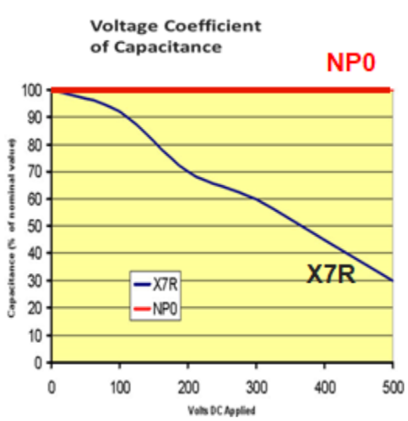


Figure 4: Voltage coefficient of capacitance

Parameter	Temperature compensation MLCC	High-dielectric constant MLCC
Paraelectric material	Titanium oxide (TiO_2) Calcium zirconate ($CaZrO_3$)	Barium titanate ($BaTiO_3$)
Relative permittivity	20 to 300	1,000 to 20,000
Temperature characteristics	+100 to -4700ppm/°C	+30 to -82%
Capacity	≤ 0.1µF	≥ 68pF
Capacitance-change when voltage input	Almost no change	Changes
Capacitance-change over time	Almost no change	Changes
Application circuits	Snubber, Time-constant High-frequency circuit, Audio	Smoothing power, Decoupling circuit

Table 1: Characteristics of MLCCs

KEY PARAMETERS FOR DESIGNING CERAMIC CAPACITORS IN SMPS CIRCUITS

INTEGRATING CAPACITORS INTO ELECTRONIC CIRCUITS: SERIES VS. PARALLEL

MLCCs can be integrated into electronic circuits in two ways: series and parallel connections. Figures 5, 6, and 7 show how to achieve this.

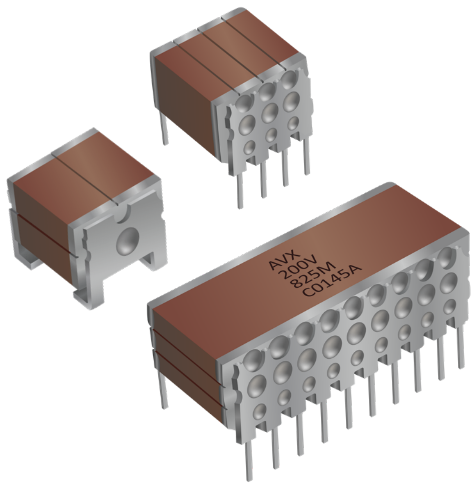


Figure 5: An example of capacitors in parallel to increase the equivalent capacitance

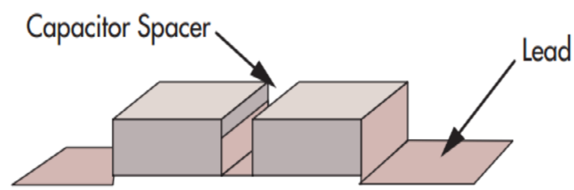


Figure 6: Using capacitors in series to meet customers' voltage rating requirements

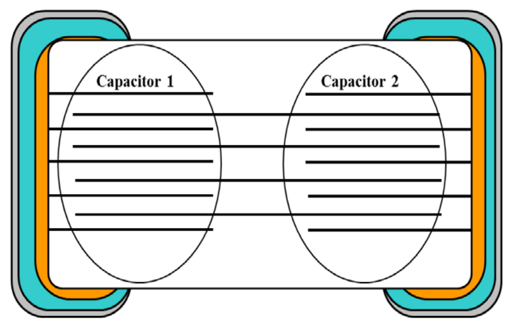


Figure 7: Flexisafe - Using capacitors in series to ensure failsafe capability

KYOCERA AVX SPICALCI 10 SIMULATION SOFTWARE

KYOCERA AVX offers the SpiCALCI 10 (the latest version of its SpiCALCI software), which is an engineering tool that simulates performance characteristics and parameters for its advanced switch-mode power supply (SMPS) multilayer ceramic capacitors (MLCCs). KYOCERA AVX created this tool to help electrical design engineers select a part that will best satisfy their application criteria.

KYOCERA AVX's SpiCalci10 software allows electrical design engineers to predict critical parameters, such as self-resonant frequency, ESR, ESL, and phase angle, for a given ambient temperature, temperature rise, and operational frequency. Moreover, designers can adjust the variables numerically, via a button slide, to model important capacitor characteristics, such as ripple current, ripple voltage, and internal temperature.

The software also helps to generate interactive graphs for further analysis of ESR and impedance vs. frequency, temperature rise vs. current, maximum current vs. frequency, maximum ripple voltage vs. frequency, phase angle vs. frequency, and capacitance changes with DC bias. The numerical data can be imported to SPICE simulation software, and the graphs can be saved and printed for presentation or sharing.

KEY PARAMETERS FOR DESIGNING CIRCUITS WITH MLCCS:

- Allowable ripple current and ripple voltage
- ESR compared to other passive components
- Temperature rise
- Thermal resistance

MAXIMUM ALLOWABLE AC RIPPLE CURRENT

In most electronic devices, the DC current signal applied to a circuit has an AC portion. This AC portion is referred to as the ripple current. The AC ripple current causes power dissipation and heating in capacitors. The power dissipated by a capacitor is a function of the ripple current and its equivalent series resistance (ESR). Heating in ceramic capacitors causes thermal gradients, which could result in degradation and cracking. Thus, ripple current capability is one of the key parameters to consider when selecting a capacitor for a specific application.

Heat Generation Characteristics of MLCCs:

When ripple current (AC) flows through a capacitor, the resistor element generates heat, and the temperature rises. However, since the MLCC offers an extremely small equivalent series resistance (ESR), the heat rise is minimal, and its ripple resistance capability is excellent. Many manufacturers specify the surface temperature of the component to be below 20 °C. Figure 8 shows a mathematical formula for calculating the maximum allowable ripple current of MLCCs:

AC Current Rating

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

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

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

Figure 8: Formulas for calculating the maximum allowable ripple current and power dissipation in an MLCC

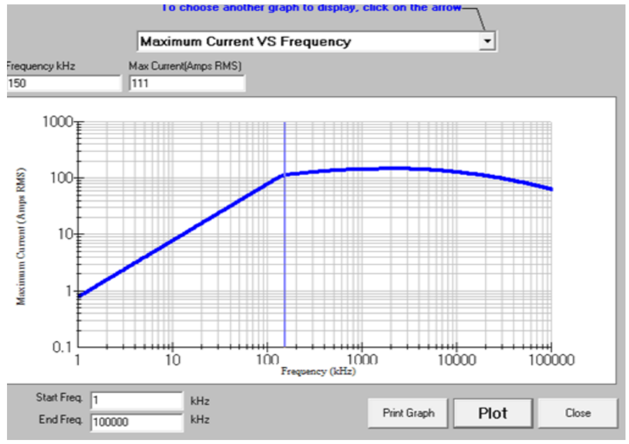


Figure 9: KYOCERA AVX SpiCalCi10 simulation of maximum current vs. frequency

Ripple Voltage (RMS) For Ceramic Capacitors:

A simple formula for calculating the maximum ripple voltage of a ceramic capacitor is:

Max Ripple Voltage

$$U_r = I_{max} \times Z = \frac{I_{max}}{\omega C}$$

Where:

Ur = maximum ripple voltage (rms)
Imax = maximum allowable rms value of ripple current
Z = impedance
ω = 2πf
C = capacitance

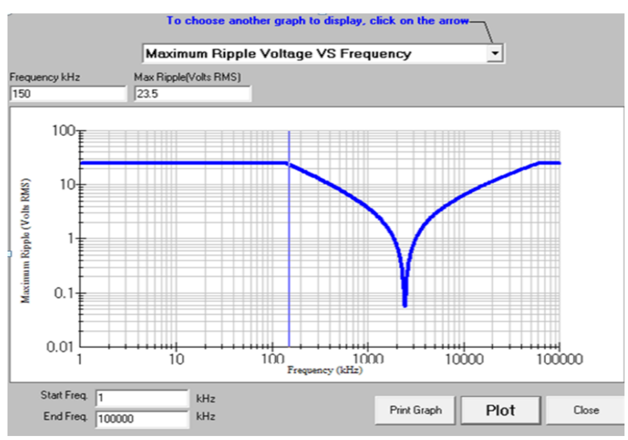
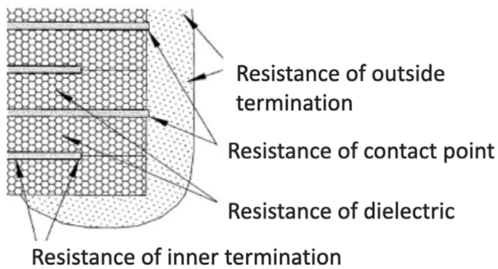


Figure 10: KYOCERA AVX SpiCalCi10 simulation of maximum ripple voltage vs. frequency

ESR CONSTITUTION

Because practical capacitors are non-ideal components, they offer some level of resistance within their constitution. When integrated in series in electronic circuits, the equivalent series resistance (ESR) is an essential parameter. Alongside the capacitance, the ESR defines a time constant for charging or discharging the capacitor and how quickly it reacts to variations in voltage, current, and ripple. Figure 11 shows the ESR constitution of a ceramic capacitor.



$$\mathrm{ESR} = \frac{\tan\delta}{\omega C} = R_S + \frac{tan\delta_0}{\omega C}$$

Figure 11: A formula for calculating the ESR of the capacitor

Where:
- tan δ = dissipation factor of the capacitor
- tan δ0 = dissipation factor of the dielectric
- C = capacitance
- Rs = series resistance
- ESR = equivalent series resistance

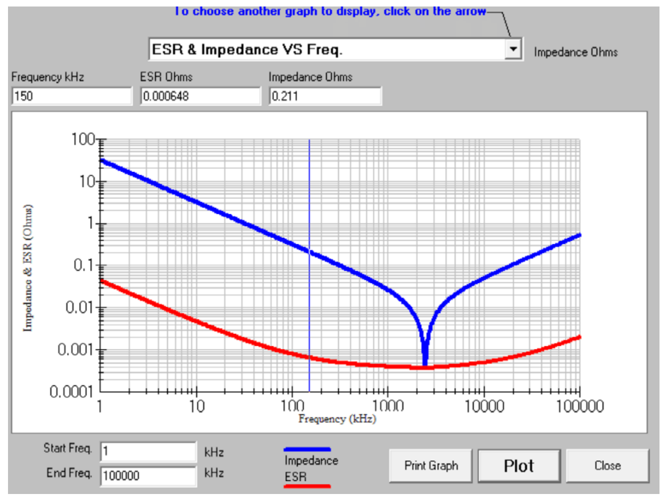


Figure 12: KYOCERA AVX SpiCalCi10 simulation of ESR and impedance vs. frequency

MAXIMUM TEMPERATURE RISE

As previously mentioned, when ripple current passes through a capacitor, power is dissipated in the form of heat, resulting in temperature rise (self-heating). Other factors include dielectric losses and the temperature of the surroundings (ambient temperature). All of these factors compound to affect the temperature of an MLCC. Since MLCCs are dependent on temperature and not current, variations in the temperature will determine the maximum ripple current. The maximum temperature rise of ceramic capacitors is usually limited to 50°C to prevent damage to the component (cracking) due to thermal gradients. For example, take a X7R MLCC with a temperature range from (-55°C to 125°C). When the circuit is operating at +25°C, the MLCC can handle enough current until the part has heated up to 125°C. However, when the same circuit is at 100°C, the ripple current would be less as there is a lower temperature differential. The KYOCERA AVX SpiCalci10 simulation below shows temperature rise vs. applied current with the following parameters:

- **Imax** = 111A(rms)
- **Irms** = 66.3A(rms)
- **ΔTmax** = 50OC
- **ΔT** = 20OC

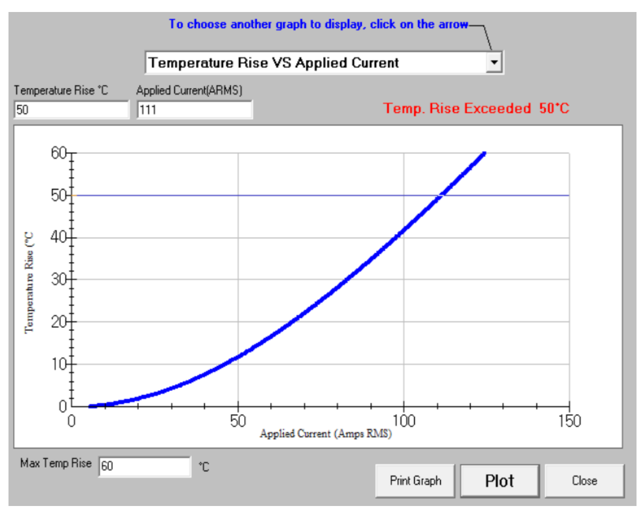


Figure 13: KYOCERA AVX SpiCalci10 simulation of temperature rise vs. applied current

RIPPLE VOLTAGE (RMS) FOR CERAMIC CAPACITORS

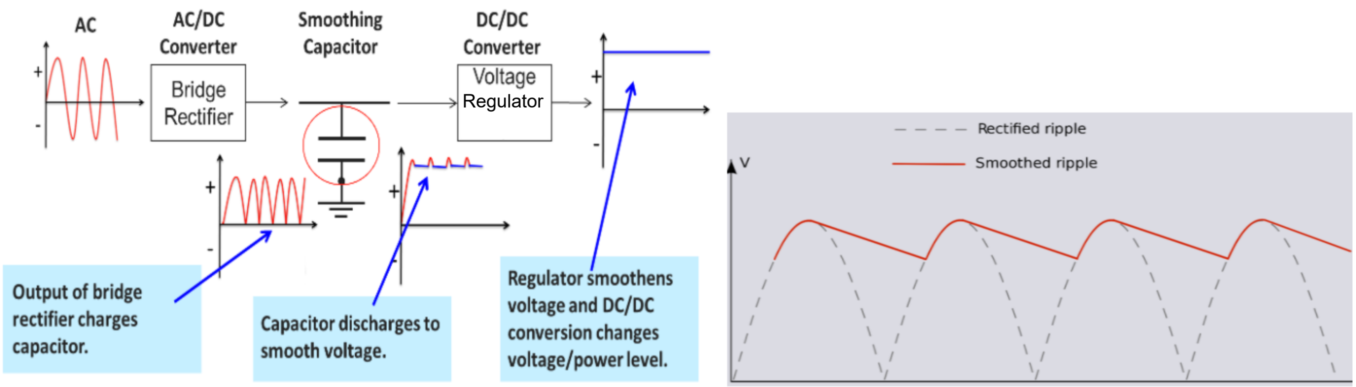


Figure 14: Smoothing/snubbing applications of ceramic capacitors

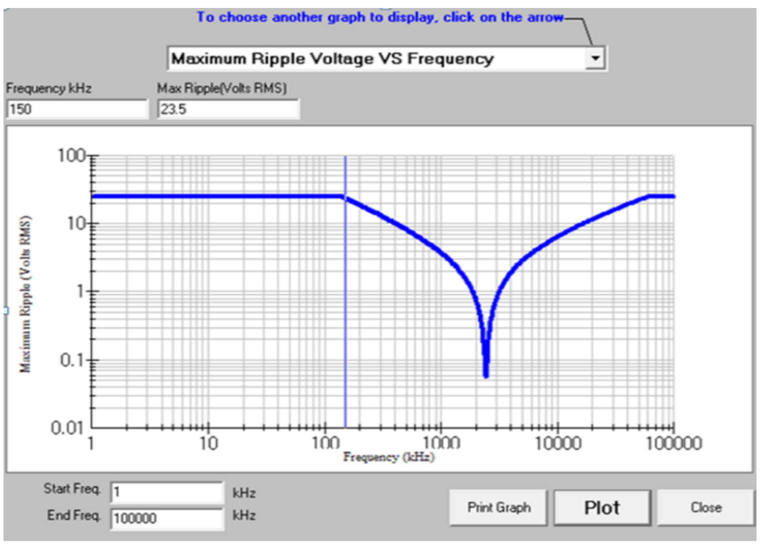


Figure 15: An KYOCERA AVX SpiCalci10 simulation of maximum ripple voltage vs. frequency

THERMAL RESISTANCE

The thermal resistance (Rth) 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. To specify the most conservative (lowest) values of ripple current capability, the thermal resistance of the MLCC is measured under still air with no heat sinking at 25°C ambient temperature. Rth will be different for each case size as it depends on both the internal construction of the capacitor (pellet size and thermal paths) and the external surface area.

Recall that thermal gradients caused by the heat generated by ripple currents can crack the ceramic chip. Electrode plates act as heat sinks, and capacitors with a high number of plates release heat from ceramic blocks more easily than components of the same size but with fewer plates.

CONCLUSION

Internal heating within ceramic capacitors affects the performance of many electronic circuits. In these capacitors, the maximum ripple current is determined by the temperature characteristics of the component. Exceeding the ripple current rating of a ceramic capacitor can significantly affect its performance. The coefficients of thermal resistance for ceramic capacitors of a given chip size vary due to differences in the number of electrode plates. Heating in ceramic capacitors causes thermal gradients that could result in physical damage such as cracking. The maximum temperature rise in ceramic capacitors is usually limited to 50°C to prevent cracking.

NORTH AMERICA
Tel: +1 864-967-2150

ASIA
Tel: +65 6286-7555

CENTRAL AMERICA
Tel: +55 11-46881960

EUROPE
Tel: +44 1276-697000

JAPAN
Tel: +81 740-321250

WWW.KYOCERA-AVX.COM