DC and AC Voltage Dependence of Ceramic Capacitors

INTRODUCTION

When selecting a ceramic capacitor, it may seem as simple as choosing the device that offers the highest capacitance per unit volume at the lowest cost, but one also needs to consider that the electrical response of certain dielectric materials can be significantly influenced by the operating conditions to which they are exposed. Selection of a low dielectric constant Class I material or a higher K Class II dielectric, can for example, have a significant impact on how that capacitor might behave when exposed to either DC or AC bias conditions. This application note covers the relationship between higher K dielectric types and voltage bias and is intended to help the engineer in making a more informed decision when engaging in the ceramic capacitor selection process.

OVERVIEW

Ceramic materials most commonly utilized for the manufacture of multilayer capacitors are either defined as being Class I dielectrics, which are considered to be very stable in nature, or Class II dielectrics, which in comparison, have higher dielectric constants and dissipation factor values and are considered less stable in nature. Class I dielectrics like NPO (COG) and negative coefficient materials, exhibit a linear relationship of polarization when exposed to an electric field and the resulting effect on dielectric constant and/or dielectric loss is considered to be negligible. Class II dielectrics like X7R, X5R, X5U and Z5U on the other hand, are comprised of ferroelectric materials and as such, they exhibit a non-linear polarization response when exposed to an electric field. This non-linear response can not only change the dielectric constant of the capacitor, it can also under AC bias, result in an increase in dissipation factor and subsequent self-heating of the capacitor. Understanding how the capacitor might behave when operated under both DC and AC bias is very important in ensuring proper capacitor selection and long term reliability of the device.

DC VOLTAGE BIAS

Unlike Class I dielectrics which exhibit a negligible shift in characteristics when exposed to DC bias, Class II dielectrics will exhibit a negative shift in dielectric constant and subsequent loss in capacitance. Dielectric Constants within this category can range from as low as 600 to as high as 22,000 and this resulting shift in capacitance, or Voltage Coefficient of Capacitance (ΔVC or VCC), tends to be more severe with higher K dielectrics. The amount of voltage applied can also impact the amount of capacitance lost, but it is important to understand that relationship between voltage and capacitance has less to do with voltage level and much more to do with the dielectric thickness and the resulting volts per mil stress applied. The engineer therefore needs to consider that the nameplate capacitance value of the capacitor being considered is specified at room temperature and 1 VRMS, that this value will most likely be lower at the actual operating voltage and that in extreme conditions capacitors can exhibit as much as 60 to 65% loss in capacitance.

Keep in mind that although Vendor A and Vendor B may both be utilizing X7R dielectric for a specific application, they may not in fact be using the same X7R formulation and differences in the dielectric constant between these materials will result in a different voltage coefficient. In addition, even if all manufacturers were to use exactly the same dielectric formulation, Vendor A will undoubtedly have design guidelines which stipulate a different dielectric thickness from Vendor B or C and that this variation in dielectric thickness will result in a different operational V/mil stress. One can't assume therefore that a 1 µF, 1000 VDC, X7R capacitor purchased from Vendor A will behave exactly the same as a 1 µF, 1000 VDC, X7R capacitor purchased from Vendor B or C.

Example: Two capacitor manufactures produce 1.0 µF, 1000 VDC capacitors using the same X7R dielectric formulation. Vendor A designs the part with a dielectric thickness of 6.7 mils, while Vendor B designs their alternative design with a dielectric thickness of 5.2 mils. If both designs are subjected to the full maximum operating voltage of 1000 VDC, what would be the resulting ΔVC for both designs?

Voltage Stress = Operating Voltage / Dielectric Thickness

	Vendor A	Vendor B
Voltage Stress	= 1000 VDC / 6.7 mils	= 1000 VDC / 5.2 mils
	= 149 volts / mil	= 192 volts / mil
Voltage Coefficient (From Figure 1)	= - 42%	= - 53%
Actual Capacitance (@ 100 VDC)	= 1.0 µF × (1 – 0.42)	= 1.0 µF × (1 – 0.53)
	= **0.58 µF**	= **0.47 µF**

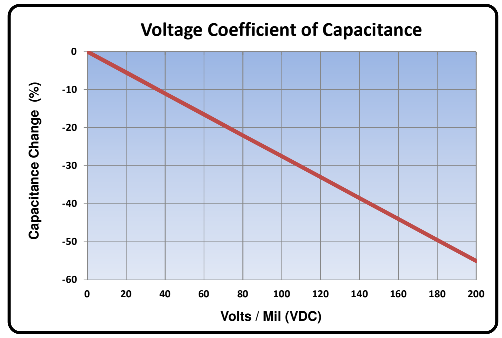

Figure 1

Military specifications like MIL-PRF-49467 have evened the playing field for suppliers inasmuch as they have defined a series of X7R dielectric subcategories that limit the amount of capacitance loss that a capacitor can exhibit due to combined changes in voltage bias (ΔVC or VCC) and operating temperature (ΔTC or TCC). It is important to recognize that ΔTC and ΔVC are in fact additive components and that a change in both operating temperature and working voltage or combinations thereof, will have a cumulative effect on the overall performance of the capacitor. BX is one such dielectric category where the maximum ΔVTC is defined as +15 / -25% across the entire operating temperature range of -55 to +125℃. Other options and their corresponding ΔVTC limits are listed in Table I.

Military Designation	DC Voltage – Temperature Coeffiecient	Voltage Characterization
BX	+15 / -25% @ WVDC & -55 to +125℃	< 500 VDC
BR	+15 / -40% @ WVDC & -55 to +125℃	≥ 500 VDC
BZ	+15 / -45% @ 60% WVDC & -55 to +125℃	≥ 500 VDC

Table I

Example: A manufacturer is intending to design a 1000 VDC capacitor to meet BR characteristics, and they are considering an X7R material with a worst case ΔTC of -10% and a ΔVC that matches the curve shown in Figure 1. With those characteristics and in order to meet a maximum ΔVTC of -40%, they would need to ensure that the total capacitance loss due to voltage bias is less than 30%. From the graph, that would require a design that has a maximum voltage stress level of 110 V/mil, something which could be achieved if they were to specify a fired dielectric thickness of 9.1 mils minimum.

Required Dielectric Thickness = Operating Voltage / Maximum Voltage Stress

= 1000 VDC / 110 V/mil

= 9.1 mils min

AC VOLTAGE BIAS INFLUENCE

As with exposure to DC voltage, Class I dielectrics display a negligible response when exposed to AC Bias. Class II dielectrics on the other hand, can display an undesirable response that generally precludes their use in AC applications. Initially they exhibit an increase in dielectric constant (K) when exposed to a low level AC signal, and a subsequent increase in capacitance. This positive shift continues as the AC voltage is increased until a material specific voltage limit is reached, at which point the trend reverses and the dielectric constant / capacitance value starts to decline. Higher K dielectrics exhibit the largest swing in ΔVC, and like those capacitors exposed to DC bias, capacitance loss can also be limited here by increasing the dielectric thickness and reducing the volts per mil stress. If a reduction in V/mil stress were the only prerequisite for predictable AC performance, this would be a simple fix, but unfortunately the inherent electrostrictive nature of Class II dielectrics will also result in a significant increase in dissipation factor and a noticeable surge in temperature rise, even at lower v/mil levels.

For an ideal capacitor operating in an AC circuit, the voltage and current are understood to be 90° out of phase from each other. In reality, there are no perfect capacitors as the resistive properties of a capacitor are not infinite and as such that portion of the current flow attributed to the resistive characteristics of the capacitor will be something less than 90° out of phase. The degree to which the actual phase angle is out of phase with the ideal is defined as the loss tangent or dissipation factor and the resulting current generated as a result causes the capacitor to dissipate energy in the form of heat. Higher K dielectrics with their higher dissipation factor, are more susceptible to heat generation and depending on the degree of heating, this inherent energy loss for Class II dielectrics can certainly affect the reliability of the device and reduce its life expectancy to something significantly less than what is required.

Although generally discouraged, some lower stress requirements can in fact accommodate the use of higher K dielectrics in an AC application. Utilization would generally need to be limited to lower frequencies of operation, like 60Hz for example, lower ripple current values and proper functionality would definitely need to be confirmed through adequate testing. Acceptable results may be possible through a significant reduction in volts per mil stress and this may be enough in certain applications to offset the adverse effects of operating under AC conditions. This approach certainly would not apply to those higher frequency applications like aircraft systems, where 400 Hz is typically utilized. In these type of applications, the higher rate of change between positive and negative polarity and the increased degree of friction between atoms, can generate more heat loss and a high likelihood that the capacitor will fail.

Something else to consider is that the inability of a ceramic capacitor to operate under AC bias will likely result in a highly destructive, catastrophic failure condition. High levels of current and heat generated in an AC short circuit situation, strongly increases the likelihood of collateral damage to the circuit board and adjacent components.

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