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Factors Affecting Temperature Rise in MLC Capacitors

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Introduction

The advantages of multilayer ceramic (MLC) capacitors over plastic film types include their smaller physical size, lower inductance, and ability to operate at higher temperatures.

These advantages make MLC capacitors well suited to high power applications, such as power converter systems in electric (EV) and hybrid electric (HEV) vehicles.

When selecting a capacitor to operate at high temperatures, it is useful to understand how its operating conditions can affect its working temperature.

This application note explores the factors that affect the working temperature of an MLC capacitor.

Background Temperature and Self-Heating

When AC (ripple) current passes through a capacitor, power will be dissipated inside the component, causing energy to be wasted in the form of heat. This mechanism is often called self-heating.

The temperature of the capacitor depends on the background (or ambient) temperature (T_A) of the immediate surroundings, and also on the temperature rise (ΔT) caused by self-heating.

Under no circumstances should $T_A + \Delta T$ be allowed to exceed the manufacturer's maximum temperature rating for the capacitor.

While T_A is often application dependent and beyond the control of the circuit designer, ΔT depends on capacitor dielectric losses, ripple current, and a range of other factors.

By keeping ΔT as low as possible, the capacitor will run cooler and have a longer operational life, and the circuit will operate more efficiently.

There is a general rule of thumb in the capacitor industry that ΔT should not exceed 20-25°C.

Dielectric Types

MLC capacitors are categorised according to the type of dielectric used.

Class I capacitors, such as COG (also known as NP0), are characterised by low dielectric losses and high stability. They are often used in resonant circuit applications.

Class II capacitors, such as X7R, offer much higher capacitance values, but are generally less stable and have higher dielectric losses. They are commonly used for applications where a stable capacitance value is less critical, such as DC link circuits.

Standard COG and X7R capacitors have a maximum temperature rating of 125°C.

Temperature Rise Comparison of COG and X7R Capacitors

Although COG capacitors generally have much lower capacitance values than X7R parts, there is some overlap in capacitance between the two ranges.

Figure 1 compares the temperature rises of COG and X7R capacitors of equal capacitance value and similar case size, as AC ripple current is increased.

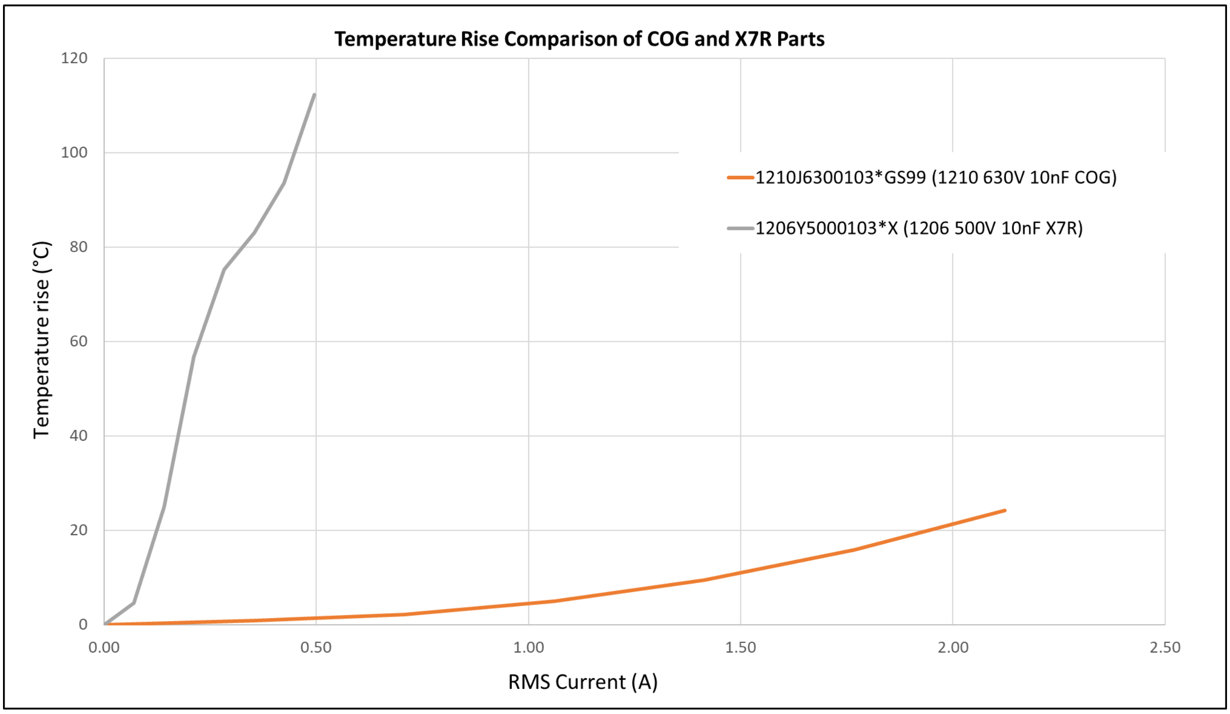

Figure 1 – Temperature rises of COG and X7R capacitors vs RMS current (frequency 75kHz, 0Vdc bias)

As would be expected, temperature rise (ΔT) increases as the amount of ripple current is increased.

Note, however, that for a given level of current, the COG capacitor exhibits a far lower temperature rise than the X7R part.

This is a direct result of the much lower losses of Class I dielectric, when compared with Class II.

The much lower self-heating effect of COG dielectric is one reason it is preferred for applications that involve high levels of AC current, such as resonant circuits in power converter systems.

X7R capacitors are commonly used where large capacitance values are required, such as smoothing and filtering circuits in DC link applications.

Effects of Current, Frequency and Voltage on Temperature Rise

The pace of development in power converter systems, particularly in EV and HEV applications, has driven the need for MLC capacitors to operate at ever-increasing currents, frequencies and voltages.

The following sections explore how these parameters affect capacitor temperature rise (ΔT) due to self-heating.

Effect of Current and Frequency on X7R Capacitors

Figure 2 shows the effect of current and frequency on temperature rise for a 1206 10nF X7R capacitor.

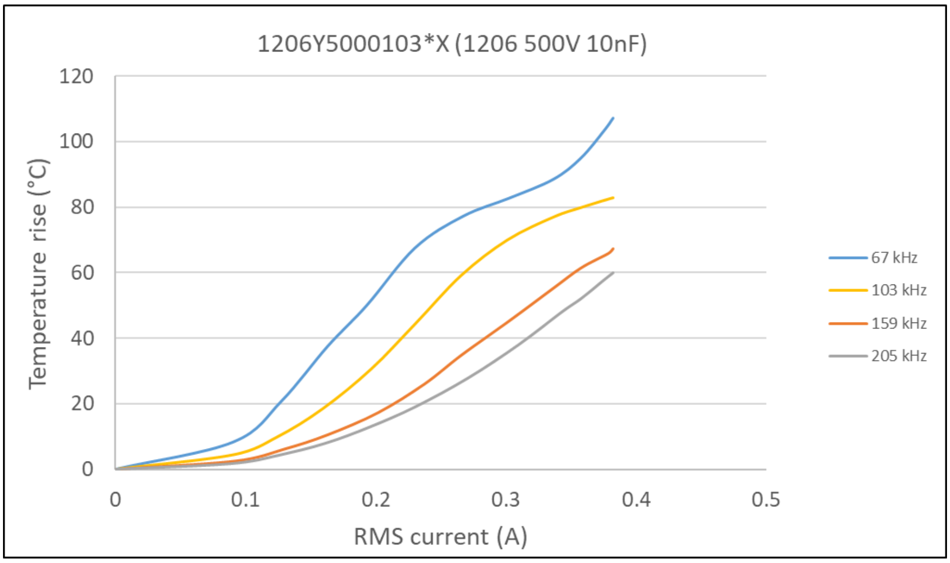

Figure 2 – Temperature rise vs current for a 1206 10nF X7R capacitor at different frequencies

If temperature rise (ΔT) is plotted against current squared, the initial slopes of the curves are approximately linear, suggesting that initial temperature rise is proportional to current squared (ΔT α I^2):

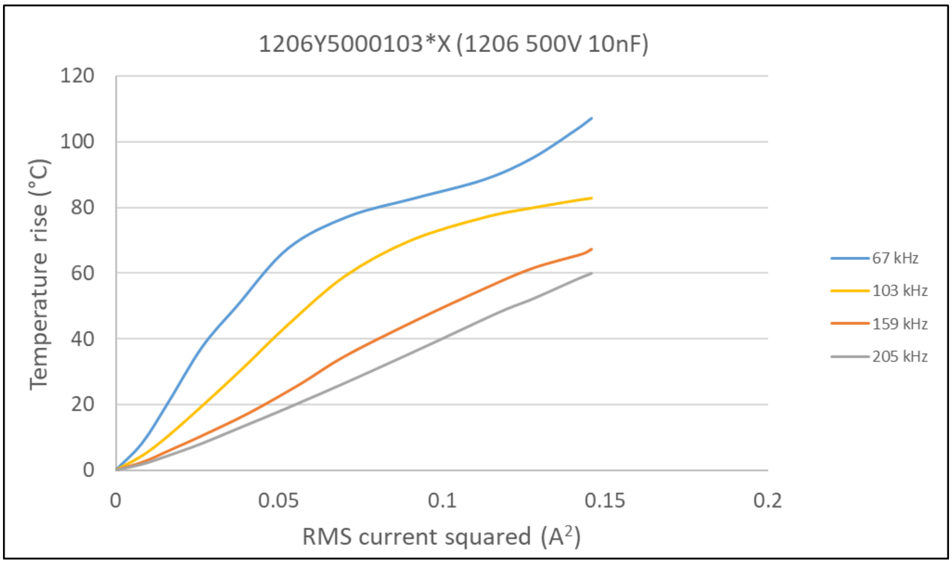

Figure 3 – Temperature rise vs current squared for the same X7R capacitor at different frequencies

This might be expected if the dielectric losses are treated as being purely resistive, since power dissipation P in a resistance R is given by the equation $P = I^2R$.

However, at higher temperatures the relationship is no longer linear:

- Above a certain level of ΔT, the gradient of each curve decreases. This occurs at approximately 70°C for the capacitor in Figure 3.
- At an even higher level of ΔT, the gradient begins to return toward its initial value, as illustrated by the 67kHz curve. For the capacitor in Figure 3, this happens when ΔT is approximately 90°C.

These results suggest there are three distinct stages to the temperature rise profile of an X7R capacitor.

Figure 3 also shows that frequency affects temperature rise.

During the initial, linear stage, doubling the frequency appears to halve the temperature rise for a given applied current. This suggests that during this stage, ΔT is inversely proportional to frequency f.

Plotting ΔT versus (I^2/f) confirms that for the 10nF X7R capacitor tested, this appears to be true for temperature rises up to approximately 60°C:

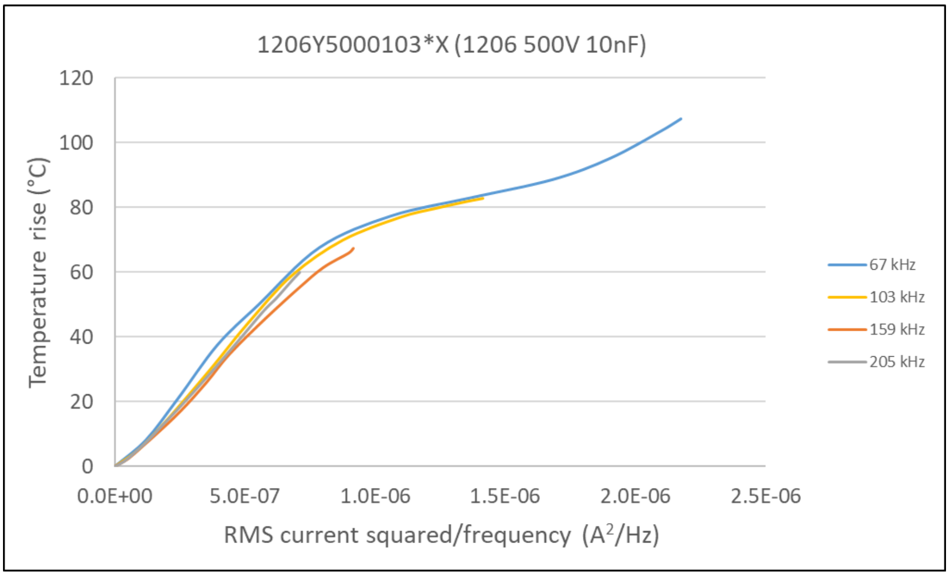

Figure 4 – Temperature rise vs [current squared/frequency] for the same X7R capacitor at different frequencies

Tests on a selection of values and case sizes have confirmed that the following relationship appears to hold true for the initial temperature rise of an X7R capacitor, for frequencies up to at least 200kHz:

$\Delta T \; \alpha \; I^2/f$

Effect of Current and Frequency on COG Capacitors

Figure 5 shows the effect of current and frequency on ΔT for a 1210 10nF COG capacitor.

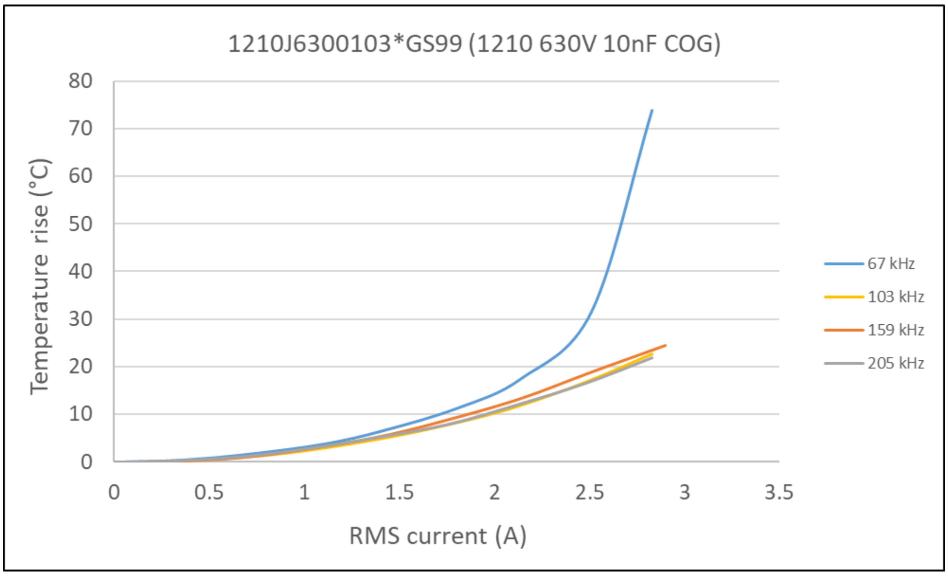

Figure 5 – Temperature rise vs RMS Current for a 1210 10nF COG capacitor at different frequencies

Note the much steeper rise of the low frequency (67kHz) curve in Figure 5, compared with the other frequencies. This is explained by the much higher AC voltages that are required to achieve the required levels of ripple current. At 67kHz, a current of only 1A rms requires the applied AC voltage to exceed the 630V voltage rating of the capacitor.

Note also that the other curves almost completely overlap, suggesting that, in contrast to X7R, frequency does not have a significant effect on the temperature rise of a COG capacitor.

Figure 6 shows the COG data re-plotted against the square of the applied current. The linearity of the 103kHz, 159kHz and 205kHz curves confirms that ΔT α I^2 over the entire range of currents measured.

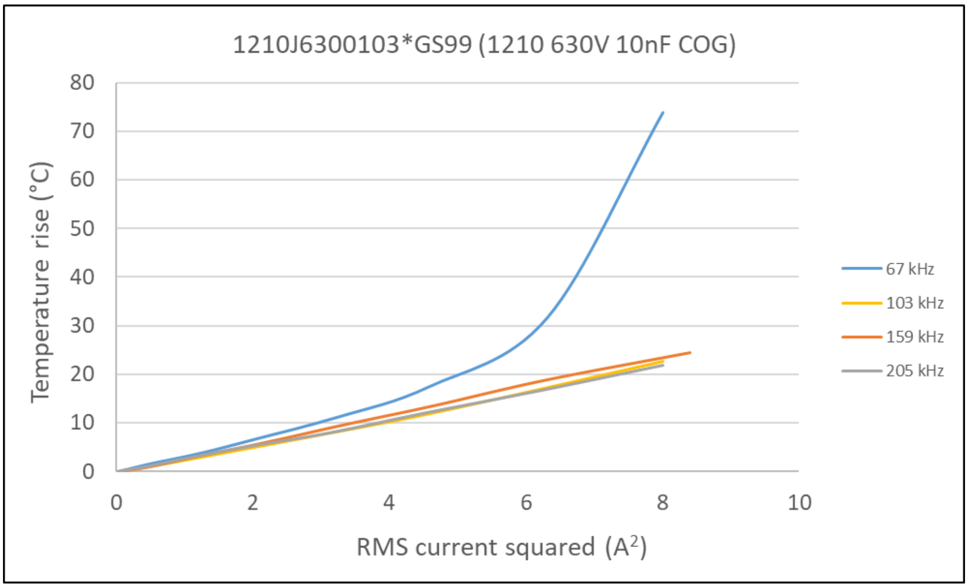

Figure 6 – Temperature rise vs RMS current squared for the same COG capacitor at different frequencies

Effect of DC Bias Voltage

The DC link circuits of power converters often use capacitors for smoothing and filtering purposes. In this application the capacitors are connected across the DC supply, and are designed to provide a path to ground for any residual AC (ripple) current.

Although the high capacitance of X7R dielectric makes it well suited to such applications, the permanent DC bias voltage across the capacitor can affect the temperature rise.

Figure 7 shows temperature rise versus AC current for a 1206 10nF X7R capacitor at different applied DC bias voltages:

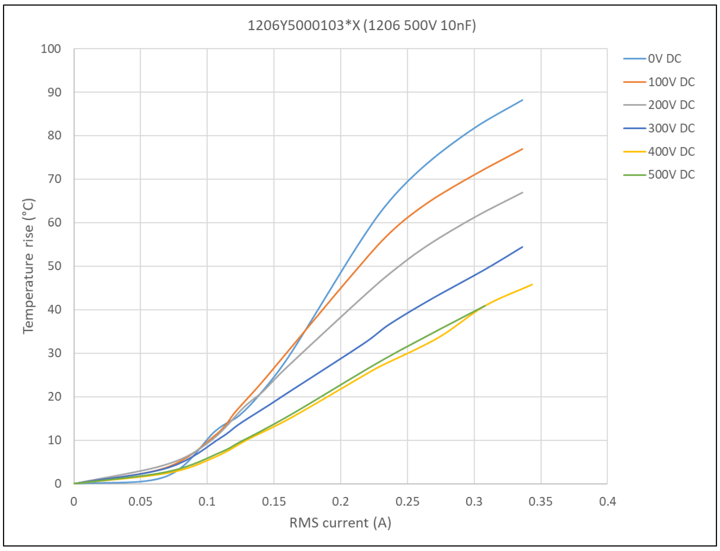

Figure 7 – 1206 10nF X7R temperature rise vs RMS current for different applied DC bias voltages (frequency 75kHz)

Note that as the DC bias is increased from zero, the temperature rise caused by a given AC current is gradually reduced. This continues until a point is reached where further bias increases have no significant effect.

Compare this with Figure 8, which shows the effect of DC bias on a 1210 10nF COG capacitor:

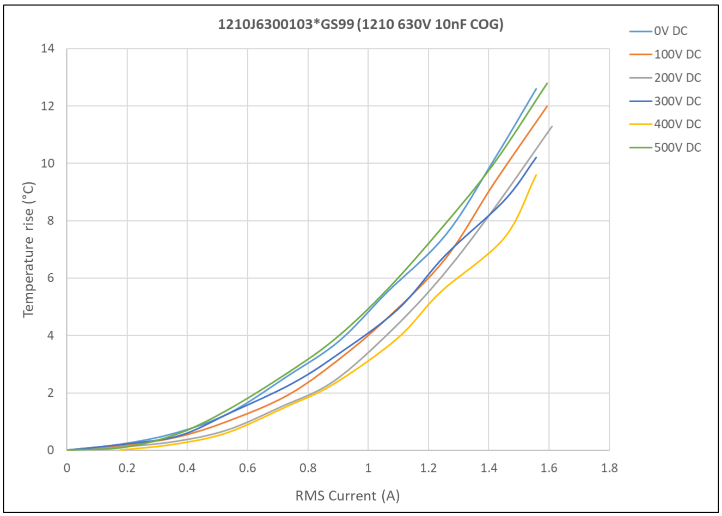

Figure 8 – 1210 10nF COG temperature rise vs RMS current for different applied DC bias voltages (frequency 75kHz)

The low temperature rise of COG parts means that measurement errors can have a significant impact. Bearing this in mind, Figure 8 suggests that any effect that DC bias may have on COG parts is small.

Effect of Background Temperature

In high power applications such as power converter systems, the heat generated by high-frequency switching circuits can significantly increase the background (or ambient) temperature surrounding a capacitor.

This increased background temperature can affect how much further the temperature of the capacitor will rise when AC current passes through it.

Figure 9 shows the effect of background temperature on a 1206 10nF X7R capacitor.

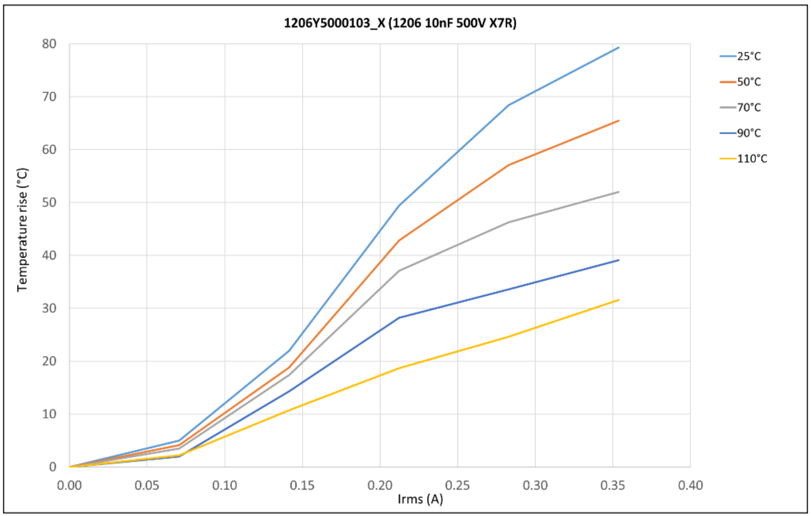

Figure 9 – 1206 10nF X7R temperature rise vs RMS current for different background temperatures (frequency 75kHz)

The graph shows that the temperature rise at the chip surface (for a given applied current) decreases as the background temperature is increased, with the effect being most pronounced at high current levels.

Figure 10 shows absolute temperature plotted against current, where:

Absolute temperature = background temperature T_A + *temperature rise* ΔT

This clearly shows that as the background temperature for this X7R capacitor is raised, high levels of ripple current have an increasingly limited effect.

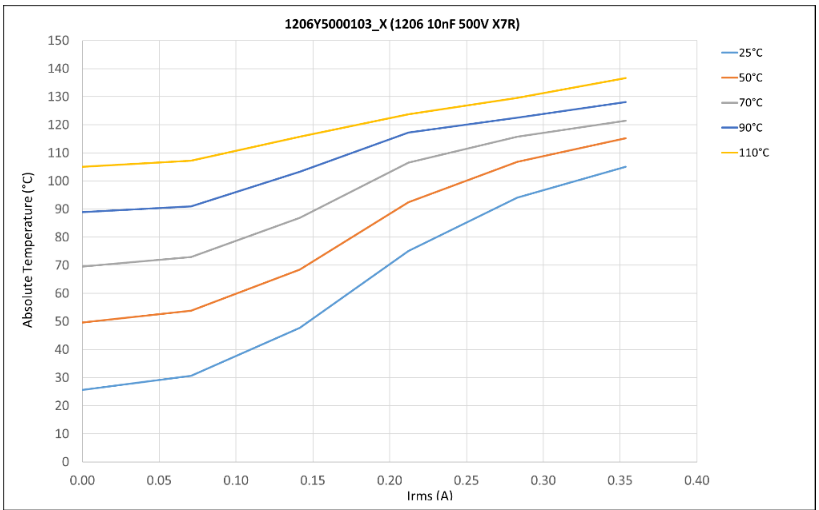

Figure 10 – 1206 10nF X7R absolute temperature vs RMS current for different background temperatures (frequency 75kHz)

Figure 11 shows how background temperature affects temperature rise in a 1210 10nF COG capacitor:

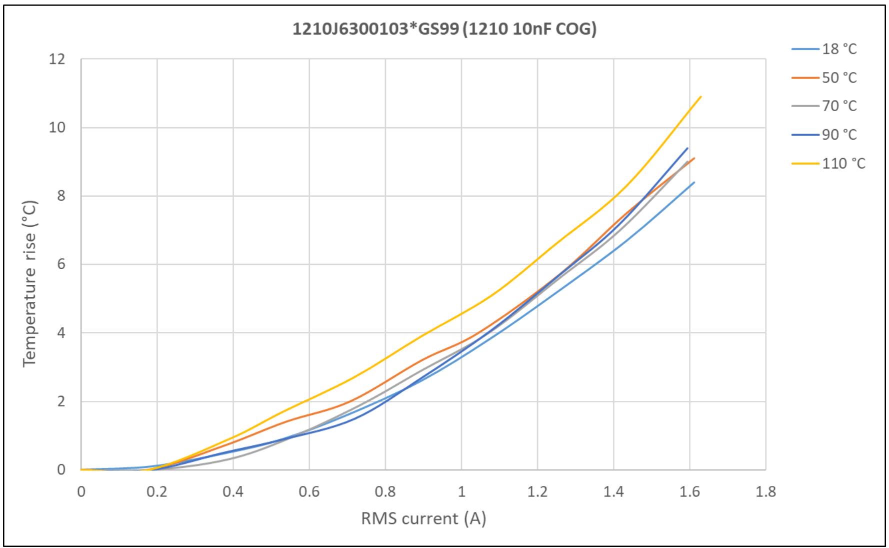

Figure 11 – 1210 10nF COG temperature rise vs RMS current for different background temperatures (frequency 75kHz)

The results show that for a COG capacitor, background temperature has significantly less effect on temperature rise than for an X7R capacitor. If there is any effect, it is too small to define accurately.

Conclusions

- The sum of the background temperature (T_A) and the temperature rise due to ripple current (ΔT) should never be allowed to exceed the maximum temperature rating of the capacitor.
- ΔT represents wasted energy. The lower its value, the longer the operational life of the capacitor and the more efficiently the circuit will operate.
- Operating conditions that can affect ΔT include the amplitude and frequency of the applied AC current, the applied DC bias voltage, and the background (ambient) temperature.
- For a given amplitude and frequency of applied AC current, a COG capacitor has a significantly lower temperature rise than an X7R capacitor of similar capacitance and case size.
- For COG capacitors, temperature rise is directly proportional to the square of the applied ripple current ($\Delta T \alpha I^2$). Frequency has no significant effect over the range of frequencies tested.
- For X7R capacitors, there are three distinct stages to the temperature rise profile. The initial temperature rise is directly proportional to the square of the applied current, and inversely proportional to frequency ($\Delta T \alpha I^2/f$) over the range of frequencies tested.
- As the DC bias voltage applied to an X7R capacitor is increased from zero, the temperature rise (for a given applied current) decreases. Eventually a point is reached where further bias increases have little or no effect.
- As the background temperature of an X7R capacitor is increased, the surface temperature rise (for a given applied current) decreases. This effect is most pronounced at high current levels.
- For COG capacitors, the effect on temperature rise of changing the DC bias voltage or the background temperature is relatively insignificant when compared with X7R parts.

More Information

The information in this application note is intended as a guide only. Our applications engineers will be pleased to assist with component selection and technical information on specific products.

For further information or technical assistance on Knowles capacitors, please contact our sales team using the contact details at the front of this Application Note.