KEMET® Corporation

Technical Update – Explanation of Ripple Current Capabilities

RIPPLE CURRENT

Ripple current refers to the AC portion of the current signal applied to a device in its application. Although this term defines an AC portion of the applied signal, it is usually in reference to the small level of variation of DC signals encountered in a power supply application. Ripple current ratings for capacitors can be somewhat arbitrary. Although the EIA has standards for calculating ripple current ratings, some manufactures use their own methods. This makes it difficult for end customers to have a one-to-one comparison. This update is intended to educate the reader on the background of ripple current capabilities, and the variables that affect them.

We start by considering a general thermo-electrical model that is applicable to all KEMET capacitor types. We then consider the specific parameter values and assumptions that are specific to tantalum, polymer, aluminum-polymer, and ceramic capacitor types.

THE GENERAL CASE FOR ALL CAPACITOR TYPES

A general formula for ripple current capability is derived from elementary physics. The power generated (P_{gen}) or rate of heat generation in a capacitor is:

$$P_{gen} = I_{rms}^2 \times ESR \quad [1]$$

where I_{rms} is the rms (root mean square) value of the ripple current (I - in amperes), and ESR is the equivalent series resistance of the capacitor (in ohms). The rate of heat removal (P_{rem}) from the capacitor is:

$$P_{rem} = \Delta T / R_{th} \quad [2]$$

where R_{th} is the thermal resistance (°C/watt) and ΔT is the temperature rise of the capacitor (°C)—the temperature difference between the capacitor and the ambient. At steady state, the rate of heat generation and heat removal balance, so the two expressions can be set equal and we can solve for the temperature rise due to the ripple current heating:

$$\Delta T = I_{rms}^2 \times ESR \times R_{th} \quad [3]$$

The higher the ripple current, ESR, and thermal resistance between the capacitor and ambient the higher the temperature rise of the capacitor. The temperature of the capacitor is directly related to failure rate—the higher the temperature of operation the higher the predicted failure rate. Ripple current has no other detrimental effect on the capacitor beyond raising its core temperature[1].

To calculate the maximum allowable rms ripple current we need to specify the maximum ΔT_{max}. Once ΔT_{max} is specified, the maximum power dissipation can be determined:

$$P_{max} = \frac{\Delta T_{max}}{R_{th}} \quad [4]$$

where P_{max} is in watts (joules/sec). Now we can combine Equations [1] and [2] into a formula to calculate the maximum allowable rms ripple current:

$$I_{max} = \sqrt{\frac{P_{max}}{ESR}} \quad [5]$$

An AC ripple current will generate an AC component of voltage across the capacitor. The rms AC voltage can be calculated from Ohm's law:

$$E_{rms} = Z \times I_{rms} \quad [6]$$

This can be converted to a peak AC voltage:

$$E_{Peak} = \sqrt{2} \times E_{rms} \quad [7]$$

CATALOG AND DATASHEET RIPPLE CURRENT RATINGS FOR TANTALUM & POLYMER TYPES

To calculate the maximum allowable ripple current, we need to specify or measure ESR, R_{th} and ΔT_{max}. For KEMET's catalog ripple current ratings, we use the maximum ESR value of the capacitor that is specified at 25°C and 100 KHz measuring frequency. Later on in this technical update, we'll show how ESR can be calculated under other conditions.

The thermal resistance in Equation [2] is a function of the internal thermal resistance of the capacitor and the thermal resistance between the capacitor and the ambient environment. The thermal resistance between the capacitor and the ambient environment is a function of the airflow over the capacitor, the surface area of the capacitor, and any heat sinking of the capacitor. To provide conservative (i.e., the lowest) values of ripple current capability, the thermal resistance of the capacitor is measured under still air conditions and no added heat sinking with a 25°C ambient temperature. Table 1 shows the measured values of R_{th} for each of the surface mount case sizes. R_{th} is different for each case size because it depends on both the internal construction of the capacitor (pellet size and thermal paths) and the external surface area.

P. Lessner, M. Prevallet, J. Prymak - August 2004

Case Code		R_{th} (°C/W)
KEMET	EIA	
R	2012-12	800
S	3216-12	333
T	3528-12	286
U	6032-15	222
V	7343-20	160
A	3216-18	267
B	3528-21	235
C	3062-28	282
D	7343-31	133
X	7343-43	121
Y	7343-40	128
E	7326-38	100
T530D	7343-31	78
T510X, T530X	7343-43	74
T510E, T530E	7260-38	70

Table 1. Thermal Resistance of Tantalum & Polymer Capacitors

Case Code		T_{Amb}=25°C, ΔT_{Max}@20°C, P_{Max}(mW)	T_{Amb}=85°C, ΔT_{Max}@16.2°C, P_{Max}(mW)	T_{Amb}=125°C, ΔT_{Max}@3.2°C, P_{Max}(mW)
KEMET	EIA			
R	2012-12	25	20	4
S	3216-12	60	49	10
T	3528-12	70	57	11
U	6032-15	90	73	14
V	7343-20	125	101	20
A	3216-18	75	61	12
B	3528-21	85	69	14
C	3062-28	110	89	18
D	7343-31	150	122	24
X	7343-43	165	134	26
Y	7343-40	156	126	25
E	7326-38	200	162	32
T530D	7343-31	255	207	41
T510X, T530X	7343-43	270	219	43
T510E, T530E	7260-38	285	231	46

Table 2. Max. Power Dissipation of Tantalum SMT Capacitors

What values should we choose for ΔT_{max}? KEMET has decided that to use a value for ΔT_{max} of 20°C for capacitors operating in an ambient environment of 25°C. This means that at this ambient, the core temperature of the capacitor is allowed rise to a temperature of 45°C. The third column of Table 2 shows the maximum power dissipation (P_{max}) at 25°C (T_{Amb}) for the different case sizes (column 3). This value is calculated by substituting the measured R_{th} in Table 2 along with a ΔT_{max} into Equation [4]. P_{max} ranges from 25 mW for the smallest case size offered by KEMET (R case) to 285 mW for the T510E, with multiple anode pellets.

What about applications with ambient temperatures above 25°C? If the ambient environment was at 120°C, for example, we would not want to allow a temperature rise of 20°C because that would allow the core temperature of the capacitor to rise to 140°C which is 15°C above the maximum recommended operating temperature (T_{max}) for a tantalum capacitor. If allowed, this could result in a high failure rate or degradation of the capacitor materials of construction. We will reduce the maximum allowable temperature rise as the ambient temperature increases.

In our catalog, we conform to an industry practice whereby at 85°C, the maximum allowed temperature rise is reduced to 16.2°C (ΔT_{max}). This corresponds to a maximum power dissipation that is 81% of the value at 25°C and a maximum rms ripple current that is 90% of the value at 25°C (column 4 of Table 2).

If ambient conditions correspond to maximum rated temperature of the component, then we are faced with something of a dilemma. Theoretically, no ripple current would be allowed because any ripple current would result in the core rising above the maximum rated temperature of the component. In the tables in our catalog, we allow a small temperature rise of 3.2°C that corresponds to a P_{max}, which is 16% of that at 25°C and a rms ripple current that is 40% of the 25°C value (last column of Table 2). While the 3.2°C temperature rise does not exactly corresponding to the "letter of the law" for the component rating, this was considered an acceptable compromise to allow the circuit designer some latitude at this maximum temperature.

Let us work though an example to help clarify the material presented above. Table 3 shows the specifications and maximum rms ripple current ratings for KEMET's T510 (MAT) series of capacitors. The 25°C maximum rms ripple current from the table for the T510X477*006AS (1st item) is 3.0 Amps. How does that compare with the maximum rms ripple current calculated from Table 1 and Equation [5]?

Substituting the value of maximum 100 KHz ESR of 30 mΩ and a maximum power dissipation of 275 mW into Equation [5] gives us an I_{max} of 3.02 amps which matches the Ta-

Capacitance µF	Case Size	KEMET Part Number	DC Leakage µA @ 25°C Max	DF % @ 25°C Max	ESR m Ω @ 25°C 100 kHz Max	Ripple Current A rms @ 25°C 100 kHz, max		
						25°C	85°C	125°C
4 Volt Rating at +85°C (2.7 Volt Rating at 125°C)								
680.0	X	T510X687(1)004AS	27.2	6.0	30.0	3.0	2.7	1.2
1000.0	E	T510E108(1)004AS	40.0	6.0	18.0	4.0	3.6	1.6
1000.0	E	T510E108(1)004AS4115	40.0	6.0	10.0	5.3	4.8	2.1
6/6.3 Volt Rating at +85°C (4 Volt Rating at 125°C)								
470.0	X	T510X477(1)006AS	28.2	6.0	30.0	3.0	2.7	1.2
680.0	E	T510E687(1)006AS	40.8	6.0	23.0	3.5	3.2	1.4
680.0	E	T510E687(1)006AS4115	40.8	6.0	12.0	4.8	4.3	1.9
10 Volt Rating at +85°C (7 Volt Rating at 125°C)								
330.0	X	T510X337(1)010AS	33.0	6.0	35.0	2.8	2.5	1.1
25 Volt Rating at +85°C (17 Volt Rating at 125°C)								
100.0	E	T510E107(1)025AS	25.0	8.0	50.0	2.4	2.1	1.0

Table 3. T510 Part Numbers and Ratings

ble 3 value (which is rounded down to 3.0 amps in 7th column). The value at 85°C is 2.7 amps (8th column), which is 90% of the 25°C value. The value at 125°C is 1.2 amps (last column), which is 40% of the 25°C value.

We have not said anything about voltage yet, and this is worth a short discussion before moving on to some more advanced topics. Tantalum capacitor manufacturers recommend that the nameplate voltage be derated beyond 85°C in a linear fashion to 67% (2/3) of that voltage at 125°C (Figure 1). The temperature that dictates this relationship is the internal temperature of the capacitor, so the application of ripple current to the capacitor can move the capacitor into a greater derating requirement due to its increased temperature. Voltage extremes created by the combined DC voltage and the ripple peak voltage (E_{Peak}) need to be considered.

The voltage need to be constrained by the following rules:

1. The DC bias voltage plus the peak AC voltage (E_{Peak}) should not exceed the maximum derated value of voltage (the value recommended at the core temperature of the capacitor).
2. The tantalum capacitor is a polar device and the DC bias voltage minus the value of peak AC voltage should not induce any reverse voltage on the capacitor.

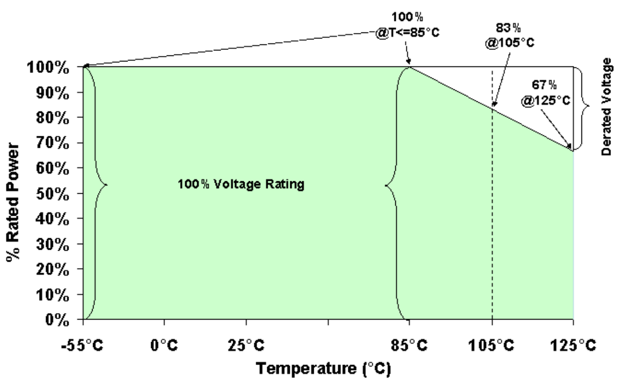

Figure 1. Voltage derating of tantalum capacitors with temperature.

BEYOND THE CATALOG AND DATASHEET FOR TANTALUM & POLYMER CAPACITORS

While the catalog and datasheets provide some guidelines for maximum allowable ripple currents, they do not deal with the complexity of variation of ESR with frequency and temperature. In addition, the values used for ΔT_{max} away from T_{max} are very conservative. This section deals with those complexities. We note that other capacitor manufacturers have already relaxed some guidelines that KEMET still utilizes in its catalog, and the information in this section will allow the circuit designer to make an "apples-to-apples" comparison between KEMET capacitors and those of other manufacturers.

The ESR of a tantalum capacitor varies with changes in temperature. For tantalum capacitors with manganese dioxide (MnO_2) electrodes, the ESR has a strong negative relation with temperature, dictated by the dominance of the cathode system on the ESR. This temperature dependence can be approximated by:

$$ESR_{Amb} = ESR_{25} \times 4^{\left[\frac{25°C - T_{Amb}}{100°C}\right]} \quad [8]$$

This shows that as temperature is increase to 100°C above 25°C, the ESR_{Amb} drops to 1/4th that of the 25°C ESR. At 100°C below 25°C, this would show the ESR_{Amb} to increase by a factor of 4 (-55°C is the limiting, or lower range for most capacitors).

For tantalum capacitors with a conductive polymer electrode, the ESR has a much weaker relationship with temperature as the cathode system now comprises a much smaller contribution of the overall ESR and the positive temperature coefficient of the metals in the structure begin to influence the effects. Slightly negative to slightly positive coefficients have been observed.

ESR also depends on frequency for tantalum and polymer capacitors. The RC ladder network combined with series and parallel resistances external to the RC ladder provides an excellent representation of the ESR of tantalum and polymer capacitors over a wide frequency range[2].

The maximum allowable temperature rise is specified in the catalog at 20°C for a 25°C ambient and 16.2°C for 85°C ambient. There is no reason why a tantalum capacitor with a T_{max} of 125°C could not have a 100°C rise at 25°C ambient or a 40°C temperature rise at 85°C ambient. This would allow a much higher I_{rms}. However, we have to note that the reliability of tantalum and polymer capacitors decreases with increasing temperature, so this tradeoff has to be carefully considered. MIL-HDBK-217F[3] provides some guidance on failure rates, and KEMET provides a program to perform those calculations[4].

A more sophisticated model would allow the value of ΔT_{max} to be selected. The value of ΔT_{max} would be automatically adjusted at higher temperatures so that the temperature of the capacitor does not exceed T_{max}. We could also adjust this model so that we could account for capacitors (like the polymer T520 series) that have maximum rated temperatures different from 125°C.

This response is shown graphically in Figure 2, with

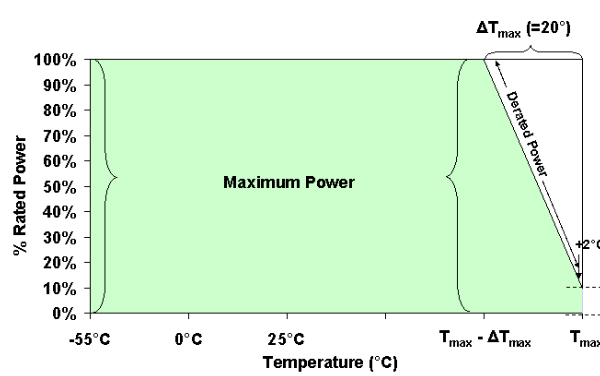

Figure 2. Derating power when approaching maximum temperature.

100% of the power dissipation allowed up to the cutoff temperature that is equal to the maximum (T_{max}) minus the allowable change (ΔT_{max}). At the maximum temperature, a 2°C rise is allowed and in between the maximum and the cutoff temperatures, a linear decay of the allowable temperature rise or power dissipation is found.

This concept may be expressed mathematically as:

$$P_{mult} = 1 - \left(1 - \frac{2}{\Delta T_{max}}\right) \times \frac{\left(T_{Amb} - \left[T_{max} - \Delta T_{max}\right]\right)}{\Delta T_{max}} \qquad [9]$$

where P_{mult} is the calculated factor that the power has to be adjusted by. Applying this factor to the Pmax of Equation [4] now yields:

$$P_{max} = P_{mult} \times \frac{\Delta T_{max}}{R_{th}} \qquad [10]$$

This adjusted value of P_{max} can now be substituted into Equation [5] to calculate I_{max}.

The discussion above shows that ESR is a complicated function of temperature and frequency (and dependent on whether the capacitor is tantalum-MnO_2 or tantalum-polymer) and the power derating depends on what assumptions are made about ΔT_{max} and what T_{max} is. This could make for very tedious hand or spreadsheet calculations. Fortunately, KEMET provides a program—KEMET Spice[5]—that includes a thermo-electrical model for calculating maximum rms ripple currents and ripple voltages as a function of temperature, frequency, and maximum temperature rise for all the tantalum capacitors that KEMET offers. Figures 3 and 4 show the output of the KEMET Spice for tantalum-MnO_2 and tantalum-polymer types of capacitors, respectively. The output is ripple current and voltage versus frequency shown for several different temperatures and over a frequency range of 100 Hz to 100 MHz. Temperature rises of 5° to 100°C can be specified. These are automatically derated at elevated ambient temperatures to prevent the core temperature of the capacitor from significantly exceeding the maximum rated temperature. In both figures, the ΔT_{max} is set at 20°C, while T_{max} for the tantalum-MnO_2 is set at 125°C, and 105°C for the tantalum-polymer.

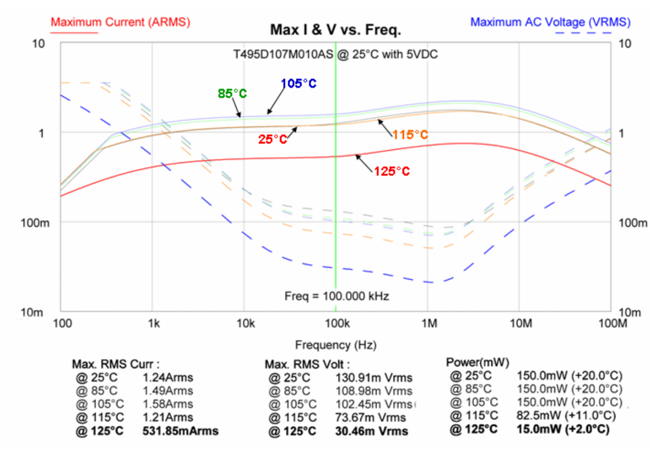

Figure 3. Screen Shot of I_{rms} & V_{rms} from KEMET Spice for a Tantalum-MnO_2 Capacitor

One note—because the KEMET Spice program uses typical values of ESR (not maximum) and a more sophisticated algorithm for derating P_{max} with ambient temperature, the values calculated using this program will, in many cases, differ from those in the catalog and datasheets. The values calculated in KEMET Spice represent more accurate values than can be put in the datasheets. In going from 25°C to 105°C for Figure 3, the negative ESR adjustment shows increasing I_{rms} capability but there is no change for Figure 4 as the tantalum-polymer has nearly no change in ESR (25°C to 85°C).

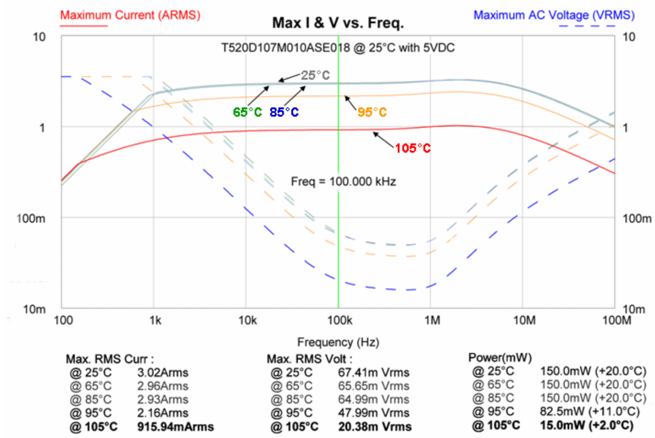

Figure 4. Screen Shot of I_{rms} & V_{rms} from KEMET Spice for a Tantalum-polymer Capacitor

One parameter that we have not discussed in detail is the thermal resistance—R_{th}. We noted that this parameter is a function of capacitor construction, size, airflow, and how the capacitor is connected to the board. As noted, the measurements in Table 1 represent very conservative values (i.e., high thermal resistances). A discussion of all these factors is beyond the scope of this note. However, a recent paper discusses these factors in more detail and provides quantitative measurements showing how construction of low ESR polymer capacitors and heat sinking can significantly reduce the thermal resistance values[6].

ALUMINUM-POLYMER CAPACITORS

Solid-state aluminum-polymer capacitors (A700 series) have the same case dimensions as the tantalum and polymer surface-mount capacitors. They obey Equations [1] through [7] in the same way as tantalum-polymer capacitors.

However, the pellet structure is replaced with a series of aluminum sheets or plates and these are welded directly to the leadframe, with no riser wire in the assembly. These differences suggest that the coefficient of thermal resistance, R_{th}, will be reduced for these devices, but we are still in the process of measuring that capability. For now, we will use the same power capability as the tantalum and polymer surface mount capacitors by chip size (Table 1) and the current calculation of Equation [5].

Like the tantalum-polymer capacitors, the ESR is weakly dependent on temperature. The thermo-electrical models for these capacitors are included in KEMET Spice.

CERAMIC CAPACITORS

Ceramic capacitors obey Equations [1] through [7] in the same way as tantalum and aluminum capacitors. However, there are a few factors the circuit designer needs to consider:

1. The coefficient of thermal resistance, R_{th}, has a strong dependence on the capacitance value in a given chip size.
2. Thermal gradients caused by the heat generated by ripple currents can lead to cracking of the ceramic chip.
3. There are no concerns about negative ripple voltage pulses as these devices are non-polar.

There are some manufacturers who claim that the thermal resistance coefficient, R_{th}, for all capacitors of a specific chip size (e.g., 0805), are all the same. Consider that the lower capacitance values of a given chip size (same dielectric and voltage rating) have fewer electrode plates than the higher capacitance ratings of that same chip size. These electrode plates act as heat extractors (heat sinks) into the thermally resistive ceramic block. The more plates into that ceramic block, the easier heat can flow out of the block. This variation of thermal resistance with capacitance is taken into account in the thermo-electrical models in KEMET Spice. There is more information related on thermal models available and dependence on capacitance layers, but is too extensive to cover here[7].

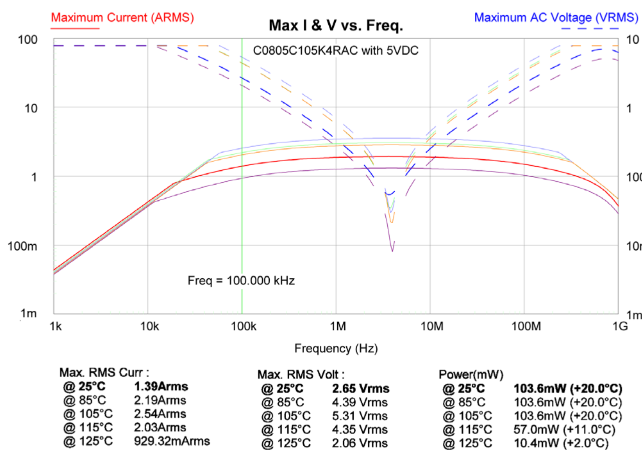

Figure 5. KEMET Spice screen of ceramic 0805 ripple capability.

Because of the potential that thermal gradients can cause shear stress and lead to cracking of ceramic capacitors, maximum temperature rises should be kept to 50°C or less.

SUMMARY

Equations [1] through [7] in this note are sufficient to describe a steady state thermo-electrical model for all capacitor types manufactured by KEMET (tantalum, aluminum-polymer, and ceramic). The complication arises in what values to use for ESR, R_{th}, and ΔT_{max} so we can calculate a maximum rms ripple current value from these equations. These parameters can be complicated functions of temperature, frequency, and maximum rated temperature of the capacitor, ambient conditions, and connection of the capacitor to the board. This note shows how simplifying assumptions are made in the catalogs and datasheet to obtain values for these parameters and how these assumptions can be reasonably extended using models that are more complex.

Confusion arises sometimes, in comparing the ripple current ratings between manufacturers because different simplifying assumptions are used to assign values to these parameters. The circuit designer needs to examine the assumptions made by different manufacturers carefully so that they may be sure that an "apples-to-apples" comparison is being made.

LIST OF SYMBOLS

E_{Peak}	Peak value of ripple voltage (volts)
E_{rms}	rms value of ripple voltage (volts)
ESR	Equivalent series resistance (ohms)
ESR_{25}	ESR at 25°C (normally 100 kHz)
ESR_{Amb}	ESR at ambient temperature
I_{max}	Maximum allowable rms value of ripple current (amps)
I_{rms}	rms value of ripple current (amps)
P_{gen}	Rate of generation of heat due to ripple current (watts)
P_{max}	Maximum power that a capacitor can dissipate (watts)
P_{rem}	Rate of removal of heat from the capacitor (watts)
R_{th}	Thermal resistance of capacitor (°C/W)
T	Temperature (°C)
T_{Amb}	Ambient temperature (°C)
T_{max}	Maximum rated temperature of the capacitor (°C)
ΔT_{max}	Maximum allowable temperature rise (°C)
ΔT	Temperature rise (°C)
Z	Impedance at frequency (ohms)

References

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3 MIL-HDBK-217F, NOTICE 2, Department of Defense, Washington, DC, February 28, 1995

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