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Current Ratings and Dissipated Power in DC and AC Applications

Capacitor specifications vary between manufacturers and it can be difficult for a design engineering selecting a capacitor to interpret the information presented in literature for use in the actual application. This application note discusses how to manipulate published capacitor ratings to the actual system requirements and determine if the capacitor will function reliably for that application.

Current ratings and dissipated power in DC applications

Capacitor current ratings can be a bit tricky and need to be understood. Take for instance a standard UL31BL506K, 50µF, ±10%, 1000 V_{dc}. The unit is rated for 52.8 A_{rms} at 10 KHz in a 65^0C ambient. The ESR of the unit is 0.00116Ω at resonant frequency 125.8 KHz with an ESL of 32 nH. The current rating is based on the hot spot or geometric center of the capacitor reaching maximum operating temperature of $+105^0$C. The UL31 series is a DC ripple filtering capacitor.

Notice that the ESR is given at resonant frequency. This is preferable since it defines the point at which X_c and X_l are equal and opposite thus canceling each other. Therefore the ESR at resonant frequency is indicative of the real resistance of the unit from electrodes, connection interfaces and parasitic losses.

To convert the ESR at resonant frequency to an equivalent ESR at any frequency find the base film DF at the frequency of operation (polypropylene at 10 KHz has an inherent DF of 0.02%) and assume the ESR at resonant frequency as the DC resistive value as shown in:

$$ESR = (DF)(X_c) + R_{electrode} + R_{parasitic}$$

$$R_{electrode} + R_{parasitic} = ESR \text{ at } F_{res} = 0.00116\Omega$$

$$ESR_{10KHz} = (0.0002)(1/(2 \text{ x } \pi \text{ x } 10{,}000 \text{ x } 50(10^{-6}))) + 0.00116 = (0.0002)(0.318) + 0.00116 = 0.0000636 + 0.00116 = \underline{0.0012236\Omega}$$

Consider the 10 KHz current rating. At 10 KHz a 50µF capacitor would have an impedance of:

$$Z = ((ESR^2 + (X_c - X_l)^2)^{1/2} = ((0.0012236^2 + (0.318 - 0.002)^2)^{1/2} = 0.316\Omega$$

Based on this impedance we can calculate the maximum ripple voltage permissible at full current of 52.8 A_{rms} as:

$$V_{rms} = I_{rms} \text{ x } Z = 52.8 \text{ x } 0.316 = 16.68\ V_{rms}$$

Thus the maximum applied power the unit can handle at 65^0C ambient and 10 KHz is:

$$P_{rms} = V_{rms} \text{ x } I_{rms} = 16.68 \text{ x } 52.8 = 880.7 \text{ watts-applied}$$

From the thermal resistance of the unit, calculate the internal temperature rise over ambient as a function of the applied power as:

$$R_{therm\text{-}applied} = \Delta T/\text{watts-applied} = (105^0C - 65^0C)/880.7 \text{ watts} = 0.045^0C/\text{watt-applied}$$

We can also calculate the thermal resistance of the unit as a function of dissipated wattage as:

$$R_{therm\text{-}diss} = \Delta T/\text{watts-dissipated} = (105^0C - 65^0C)/(52.8^2 \text{ x } 0.0012236)\text{watts} = 40^0C/3.41$$

$$= 11.73^0C/\text{watt-dissipated}$$

Current ratings and dissipated power in AC applications

When considering AC capacitors it is important to consider the carrier or line frequency at which they operate. Take for instance an inverter output capacitor with PWM control. For this example we will choose a standard 5MPA2206J, 20µF, ±5%, 530 V_{rms} at 60 Hz. This unit is rated for a total of 46.8 A_{rms} (carrier and PWM combined) based on an ESR of 0.0019Ω at a resonant frequency of 161.2 KHz and ESL of 48.7 nH.

First consider the current relative to the line frequency at 60 Hz (polypropylene at 60 Hz has an inherent DF of 0.02%):

$$ESR = (DF)(X_c) + R_{electrode} + R_{parasitic}$$

$$R_{electrode} + R_{parasitic} = ESR \text{ at } F_{res} = 0.0019\Omega$$

$$ESR_{60Hz} = (0.0002)(1/(2 \times \pi \times 60 \times 20(10^{-6}))) + 0.0019 = \underline{0.02843\Omega}$$

$$Z = ((ESR^2 + (X_c - X_l)^2)^{1/2} = ((0.02843^2 + (132.63 - 0.0000184)^2)^{1/2} = 132.63\Omega$$

$$I_{rms} = V_{rms}/Z = 530 / 132.63 = 4\ A_{rms} \text{ at } 60\text{ Hz}$$

Now consider the PWM ripple superimposed on the 60 Hz carrier. For purposes of illustration we will assume a PWM frequency of 10 KHz.

$$ESR = (DF)(X_c) + R_{electrode} + R_{parasitic}$$

$$R_{electrode} + R_{parasitic} = ESR \text{ at } F_{res} = 0.0019\Omega$$

$$ESR_{10KHz} = (0.0002)(1/(2 \times \pi \times 10{,}000 \times 20(10^{-6}))) + 0.0019 = \underline{0.00206\Omega}$$

$$Z = ((ESR^2 + (X_c - X_l)^2)^{1/2} = ((0.00206^2 + (0.796 - 0.00306)^2)^{1/2} = 0.793\Omega$$

Based on this impedance we can calculate the maximum ripple voltage permissible at full current of 46.8 A_{rms} – 4 $A_{rms\text{-}60Hz}$ = 42.4 A_{rms} as:

$$V_{rms} = I_{rms} \times Z = 42.4 \times 0.793 = 33.6\ V_{rms}$$

Thus the maximum applied power the unit can handle at 65^0C ambient with line frequency and 10 KHz PWM is:

$$P_{rms} = (V_{rms} \times I_{rms})_{60Hz} + (V_{rms} \times I_{rms})_{10KHz} = (530 \times 4) + (33.6 \times 42.4)$$
$$= 3544.6 \text{ watts-applied}$$

To calculate the dissipated wattage both frequencies must be considered. First consider the 60 Hz component. The DF of the assembled capacitor at 60 Hz is very close to the base film DF. AC capacitors are produced with a heavier electrode deposit than high energy density DC capacitors and at frequencies below 1,000 Hz the assembly and film DF are approximately the same in a well constructed unit.

$$P_{applied\text{-}60Hz} = 530V_{rms} \times 4A_{rms} = 2120 \text{ watts-applied}$$

$$P_{diss\text{-}60Hz} = P_{applied} \times DF_{assembly\text{-}60Hz} = 2120 \times 0.0002 = 0.424 \text{ watts-dissipated}$$

Now calculate the dissipated wattage at the PWM frequency as shown in the DC example for the UL31:

$$P_{applied\text{-}10KHz} = 33.6V_{rms} \times 42.4A_{rms} = 1424.6 \text{ watts-applied}$$

$$P_{diss\text{-}10KHz} = I_{rms}^2 \text{ x } ESR_{10KHz} = 42.4^2 \text{ x } 0.00206 = 3.7 \text{ watts-dissipated}$$

Now the total thermal resistance can be calculated from the combination of the two frequencies:

$$R_{therm\text{-}applied} = \Delta T/\text{watts-applied} = (105^0C - 65^0C)/1424.6 \text{ watts} = 0.028^0C/\text{watt-applied}$$

$$R_{therm\text{-}diss} = \Delta T/\text{watts-dissipated} = (105^0C - 65^0C)/(0.424 + 3.7))\text{watts} = 40^0C/4.12 = 9.69^0C/\text{watt-dissipated}$$

It should be noted here that the internal hot spot temperature for the 5MPA2206J used in the example above is +105^{0}C. However the literature relates the maximum operating temperature for the line as +85^{0}C. The operational temperature range is conservatively rated to +85^{0}C because the line is intended for AC applications with full voltage rating over the operating range.

It should also be noted here that the AC line is referred to a line frequency of 60 Hz. The capacitor however will function at other line frequencies but caution must be used to prevent overheating the capacitor from line current at higher frequencies. For example consider the same 5MPA2206J capacitor in the example above. If the unit is used for 400 Hz AC voltage the impedance is first calculated:

$$ESR = (DF)(X_c) + R_{electrode} + R_{parasitic}$$

$$R_{electrode} + R_{parasitic} = ESR \text{ at } F_{res} = 0.0019\Omega$$

$$ESR_{400Hz} = (0.0002)(1/(2 \text{ x } \pi \text{ x } 400 \text{ x } 20(10^{-6}))) + 0.0019 = \underline{0.00588\Omega}$$

$$Z = ((ESR^2 + (X_c - X_l)^2)^{1/2} = ((0.00588^2 + (19.89 - 0.000122)^2)^{1/2} = 19.89\Omega$$

The maximum line current that can be produced at 400 Hz at a maximum voltage of 530 V_{rms} is:

$$I_{rms} = V_{rms}/Z = 530/19.89 = 26.65 \ A_{rms}$$

At 85^{0}C the 5MPA2206J capacitor is rated for 36.6 A_{rms}. Therefore at 85^{0}C this unit can operate at full rated voltage at 400 Hz. The remaining 10 KHz PWM capability is calculated by first determining the heat rise relative to the line frequency:

$$P_{applied\text{-}400Hz} = 530V_{rms} \times 26.65A_{rms} = 14{,}122.67 \text{ watts-applied}$$

$$P_{diss\text{-}400Hz} = P_{applied} \times DF_{assembly\text{-}60Hz} = 14{,}122.67 \times 0.0002 = 2.82 \text{ watts-dissipated}$$

$$2.82 \text{ watts-dissipated} \times 9.69^0C/\text{watt-dissipated} = 27.3^0C$$

If the unit is functioning in a 65^0C ambient then there is allowance for a 40^0C temperature rise in the core before passing the maximum polypropylene operating temperature of 105^0C. Heating due to the 400 Hz line at 530 V_{rms} is 27.3^0C thus leaving a maximum heat rise of $40^0C – 27.3^0C = 12.7^0C$ for the 10 KHz PWM current. The maximum 10 KHz PWM current is calculated by:

$$12.7^0C/(9.69^0C/\text{watt-dissipated}) = 1.31 \text{ watts-dissipated}$$

From the 10 KHz ESR calculated before we determine:

$$P_{diss\text{-}10KHz} = I_{rms}^2 \times ESR_{10KHz}$$

$$1.31 \text{ watts-dissipated} = I_{rms}^2 \times 0.00206$$

$$I_{rms} = (1.31/0.00206)^{1/2} = 25.2 A_{rms}$$

The maximum ripple voltage is then calculated as:

$$V_{rms} = I_{rms} \times Z = 25.2 \times 0.793 = 19.98 V_{rms}$$

The total power dissipated between the 400 Hz line and the PWM ripple is 2.82 + 1.31 = 4.13 watts-dissipated. By comparison it is found that this is the same power that is dissipated in the 60 Hz example. However note that the maximum current stated in the literature at 65^0C is 46.8 A_{rms} and the total applied in the 400 Hz example is 26.65 + 25.2 = 51.85 A_{rms}. However this is permissible since the terminal can support the 52 amps easily and the total power is the same. Consult the capacitor design engineer when the total current will exceed the published limit.

One other note to the above example is the voltage. The 5MPA2 line is intended for PWM inverter outputs and is listed with a 530 V_{rms} maximum AC voltage and a 750 V_{dc} maximum peak or DC voltage. In the examples above it was ignored that the 530 V_{rms} maximum AC voltage is exceeded when the ripple voltage is added to the line. The 530

V_{rms} maximum rating refers to a clean sine wave with no ripple. Generally the applications are 380 – 440 V_{rms} lines. However in no case can the peak voltage of the line and ripple exceed the 750 V_{dc} rating. For the 60 Hz example the total peak voltage is $(530 + 36.795) \times 2^{1/2} = 801.6$ volts peak which exceeds the 750 V_{dc} limit. Once again, the application is best to discuss with the capacitor design engineer as it is impossible to express the variables of every possible application in the literature.

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