Deriving Life Multipliers for Electrolytic Capacitors

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Aluminum electrolytic capacitors are routinely used as input bus capacitors in the power supply sections of electronic equipment such as motor drives, UPS systems, and welders. Most of these capacitors fail eventually from wearout. This article offers a brief explanation of how capacitor manufacturers quantify the effects of applied voltage, ripple current, frequency, ambient temperature, and airflow on capacitor life.

The general capacitor life equation is

$$L = L_B \times f_1(T_M - T_C) \times f_2(V) \qquad (1)$$

where L is the life estimate in hours, L_B is the base life at elevated maximum core temperature T_M, T_C is the actual core temperature in the application of interest, and V is the applied DC voltage. This equation shows that there are three factors in the life equation: base life, temperature, and DC voltage.

Base life L_B is the expected service life at full rated voltage and temperature T_M. A typical rating is L_B = 5,000 hours at T_M = 108 ºC. End of life is usually defined in terms of parametric changes in capacitance, effective series resistance (ESR), and leakage current. One of the most recent industry efforts for standardizing these tests and limits was published by the EIA and is available as EIA IS-749.

The effect of temperature on capacitor life is dictated by the Law of Arrhenius, which is

$$f_1 = e^{\frac{Ea}{k}\left(\frac{1}{T_C} - \frac{1}{T_M}\right)} = e^{\frac{Ea}{k}\left(\frac{T_M - T_C}{T_C T_M}\right)} \qquad (2)$$

For anodic alumina the activation energy Ea = 0.94 eV. The Boltzmann constant k = 8.62e-5 eV/K, so we have Ea/k = 1.091e4 K. The Arrhenius equation for the temperature life factor f_1 may be rearranged as follows to establish the familiar "doubles every 10 ºC" rule. If we define $\Delta T = T_M - T_C$ and choose $T_C T_M$ based on the normally highest usage electrolytic temperature range of 125 ºC (398 K), we have

$$f_1 = e^{\frac{1.091e5}{(398)^2}\left(\frac{\Delta T}{10}\right)} \cong e^{\ln 2 \times \Delta T / 10} = 2^{\Delta T / 10} > 1 \qquad (3)$$

The temperature rise ΔT is calculated as

$$\Delta T = P\theta = I^2 R\theta \qquad (4)$$

where P is the dissipated power, I is the AC RMS ripple current, R is the ESR, and θ is the thermal resistance from core to ambient, which is the sum of the core-to-case thermal resistance θ_{CC} and the case-to-ambient thermal resistance θ_{CA}.

$$\theta = \theta_{CC} + \theta_{CA} \cong \theta_{CC} + 500A^{-7/8}(v+1)^{-2/3} \qquad (5)$$

where A is the surface area of the capacitor (cm^2) and v is the airflow velocity (m/s) near the capacitor. A fairly good model for the ESR is

$$R = R_S(T_C) + D/2\pi fC \qquad (6)$$

where R_S is the ohmic loss from electrolyte, tabs and foils, and $D/2\pi fC$ is the dielectric loss— D is the dissipation factor $D \cong 0.013$, f is the frequency (Hz), and C is the capacitance (F). R_S usually possesses a significant negative temperature coefficient (1-2% per ºC near room temperature) due to the electrolyte viscosity's change with temperature and its associated effect on the ionic mobility of the conductive species within the electrolyte. D usually has a positive temperature coefficient (0.3%/ºC is typical).

The voltage multiplier f_2 arises from the lowered stress on the dielectric when the applied DC voltage Va is reduced. In electrolytic capacitors, applying DC voltage actually drives a beneficial, ongoing electrochemical reaction that heals defects in the anode dielectric. However, at higher stress levels such as when the temperature is near T_M, the additional leakage current from operating near

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the maximum voltage rating Vr may cause enough electrochemical degradation and hydrogen gas evolution as to reduce the life of the capacitor. Therefore a reduction in the applied DC voltage may extend the life of the capacitor, especially at elevated temperatures in capacitors that are tightly sealed. The effect of voltage derating on life has been modeled with linear fit and with power laws of the voltage ratio x=Va/Vr with exponents from 0 (no effect) to 6. See Figure 1.

From these equations we can readily derive life or ripple current multipliers for derated ambient temperature, derated ripple current, airspeeds other than natural convection, and frequencies other than the standard 100 or 120 Hz, starting with the capacitance, ESR, and ripple current ratings. Remember not to try to “have your cake and eat it, too” by using both the life and ripple multipliers simultaneously! The ripple multipliers are approximately as follows:

$$\sqrt{\frac{T_M - T_A}{T_M - T_R}} \qquad \text{Ambient temperature} \qquad (7)$$

$$\sqrt{\frac{R_S + D/2\pi f_R C}{R_S + D/2\pi f C}} \qquad \text{Frequency} \qquad (8)$$

$$\sqrt{\frac{\theta_{CC} + 500A^{-7/8}(v+1)^{-2/3}}{\theta_{CC} + 500A^{-7/8}(v_R+1)^{-2/3}}} \qquad \text{Air speed} \qquad (9)$$

Large core-to-ambient temperature rises from high ripple current shorten life more than (7) suggests because increasing ESR accelerates the temperature rise. In these equations, T_R is the rated ambient temperature at which the rated ripple is specified, f_R is the frequency of the rated ripple, and v_R is the rated air velocity (usually 0-1 m/s). Figure 2 shows calculated life multipliers for the case of a 270 µF 400 Vdc snapmount capacitor versus f & (Ia/Ir) and versus v & T_A.

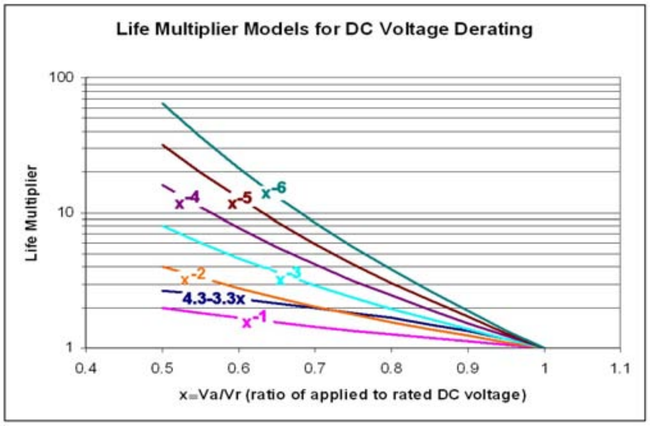

Figure 1: DC voltage life multipliers from various capacitor manufacturers. CDE generally uses 4.3-3.3Va/Vr.

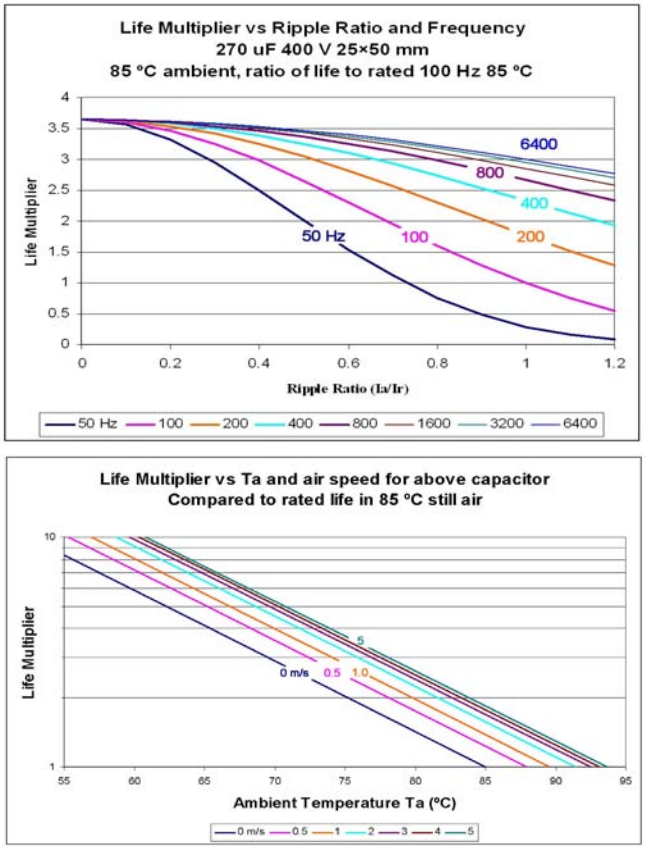

Figure 2: Life multipliers demonstrating the effects of varying ripple amplitude and frequency (top) and varying air speed and ambient temperature (bottom).

Sam G. Parler, Jr., P.E., was born in South Carolina, USA, in 1961 and studied electrical engineering at Clemson University. After receiving his BSEE degree in 1984, he worked for Union Switch & Signal. From 1988 to 1991 he directed a Strategic Defense Initiative contract for Cornell Dubilier, developing high energy density capacitors for military applications. In 1994 he co-founded Maven Capacitor Corporation (presently owned by St. Jude Medical) to develop and produce high energy density aluminum electrolytic pulse capacitors for implantable defibrillators. Mr. Parler has served as Director of Research and Development for Cornell Dubilier since 1996. His topics of capacitor research include thermal modeling, impedance modeling, life and reliability modeling, and ways to improve capacitor performance.

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