

Selecting and Applying Aluminum Electrolytic Capacitors for Inverter Applications

Sam G. Parler, Jr.
Cornell Dubilier

Abstract— Aluminum electrolytic capacitors are widely used in all types of inverter power systems, from variable-speed drives to welders to UPS units. This paper discusses the considerations involved in selecting the right type of aluminum electrolytic bus capacitors for such power systems. The relationship among temperature, voltage, and ripple ratings and how these parameters affect the capacitor life are discussed. Examples of how to use Cornell Dubilier’s web-based life-modeling java applets are covered.

Introduction

One of the main application classes of aluminum electrolytic capacitors is input capacitors for power inverters. The aluminum electrolytic capacitor provides a unique value in high energy storage and low device impedance. How you go about selecting the right capacitor or capacitors, however, is not a trivial matter. Selecting the right capacitor for an application requires

a knowledge of all aspects of the application environment, from mechanical to thermal to electrical. The goal of this paper is to assist you with selecting the right capacitor for the design at hand.

Capacitor ripple current waveform considerations

Inverters generally use an input capacitor between a rectified line input stage and a switched or resonant converter stage. See Figure 1 below. There is also usu-

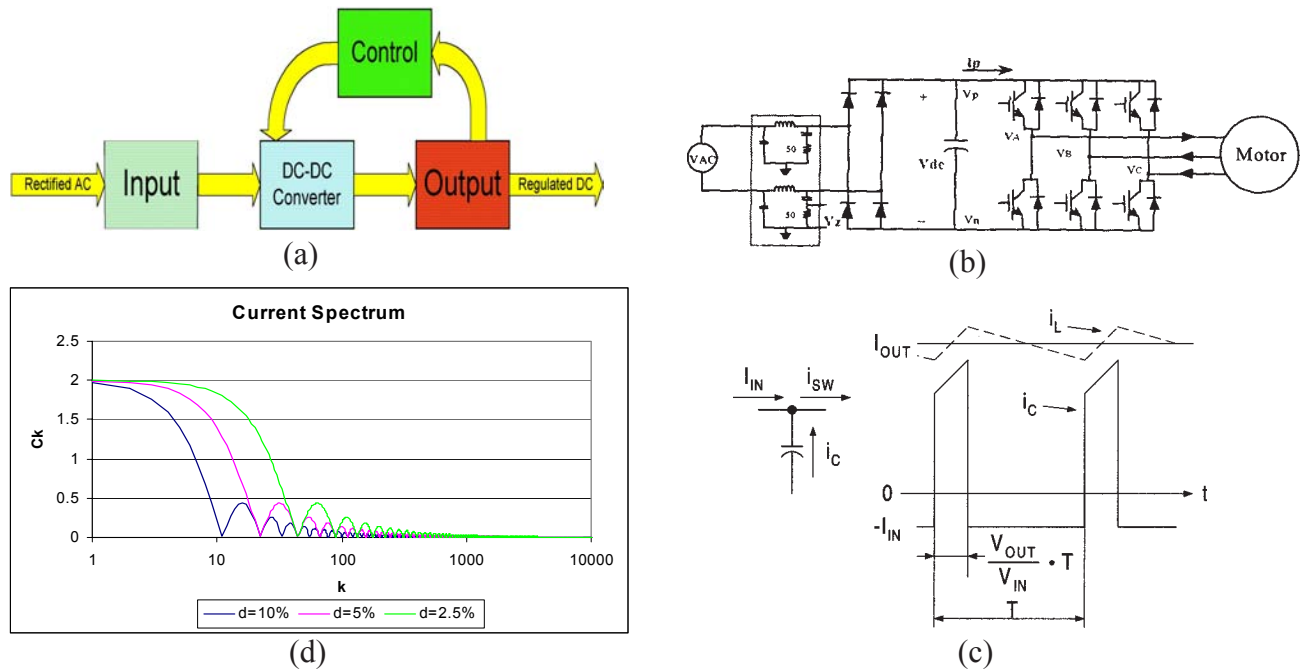


Figure 1: Inverter schematics. Clockwise: (a) block diagram of a typical DC power supply featuring an inverter stage, (b) motor drive inverter schematic shows the rectification stage, (c) typical inverter capacitor current waveforms, (d) relative capacitor ripple current frequency spectrum for various charge current duties ($d=I_c/I_L$).

ally an output filter capacitor. There are many power supply topologies, and this paper is not meant to serve as a power supply design primer. Choose your topology based on your design philosophy and the constraints of the application. As far as the capacitor is concerned, keep in mind that the RMS capacitor ripple current I_r is affected by the duty d , defined as the ratio of peak charge current I_c to average load current I_L approximately as:

$$I_r = I_c \sqrt{d/(1-d)} = I_L \sqrt{(1-d)/d} \quad (1)$$

For practical duty cycles of 5-20%, this leads to ripple currents that are 2-4× the DC current output by the capacitor. The duty d may well affect the capacitor selection, as low-duty, high-peak-current charging circuits subject the capacitor to higher RMS ripple current. Note that the spectral content of the ripple current shifts with the duty cycle as shown in Figure 1(d). Depending on the shape of the capacitor ESR (effective series resistance) vs frequency curve, changes in the current duty cycle may lead to capacitor power dissipation that is proportional to the RMS ripple current, proportional to the square of the RMS ripple current, or somewhere between these two extremes.

Power range

Power supplies below a hundred watts generally use surface-mount capacitors. These devices will be discussed in a later paper. In the higher-power applications discussed in this paper, the input capacitor is usually aluminum electrolytic. This paper will focus on three main capacitor types used in higher-power inverter

applications: snapmount, plug-in, and screw-terminal capacitors. See Figure 2 below and Table 1 on page 3. Small snap-in's and radials are often used in the 100-1000 W range, and larger snapmount capacitors and snap-in farms are used in the 1-20 kW range. Screw-terminal and plug-in capacitors also begin seeing use in the 500 W and higher power ranges.

Mechanical and assembly issues

Screw-terminal and plug-in capacitors offer a more rugged package for higher vibration and shock performance for very little additional cost compared to snapmount capacitors. A little additional assembly effort is required in using plug-in or screw-terminal capacitors. For screw-terminal capacitors, proper thread torque needs to be monitored. A large bank of snapmount plug-in capacitors might make sense when a large circuit board topology is desired and can be afforded, or if extremely low inductance is desired. However, should there be a capacitor problem, capacitor location and replacement might be difficult, and an expensive circuit board and



Figure 2(a, left; b, center; c, right): Snap-in capacitor (left), plug-in capacitor (center), and screw-terminal capacitor (right).

bank might be difficult or impossible to rework. Screw-terminal capacitors can be circuit-board mounted, or alternatively, a laminated or discrete bus structure may be employed. Screw-terminal capacitors generally use a heavier-duty paper-electrolyte pad compared to the snapmount capacitors. This often allows them to operate at lower failure rates in banks with the same stored energy.

85 °C versus 105 °C ratings

As far as the thermal environment is concerned, all three of these capacitor types have ratings availabilities from 85 °C to 105 °C with ripple. In general, 105 °C-rated capacitors give longer life and/or higher ripple current capability. The main difference in construction between the 85 °C and the 105 °C capacitors is in the anode foil. The anodization voltage (formation voltage) is higher for the 105 °C capacitors. Since the anode capacitance per foil area is lower at higher anodization voltages, this usually means that there is a little less capacitance

available in the same case size in a 105 °C rated capacitor compared to its 85 °C counterpart.

Capacitance versus voltage rating

Capacitance per surface area varies approximately inversely with the square root of the cube of the rated voltage. This concept allows you to calculate the rated capacitance at a rated voltage in a given case size when you know another rated capacitance/voltage.

$$C_1 V_1^{1.5} = C_2 V_2^{1.5} \quad (2)$$

For example, if you know that we offer 1.2 F at 20 V in a 3x8.63” package, you can figure that at a 400 V rating we should be able to offer about $1.2 \times (400/20)^{1.5} = 0.013 \text{ F} = 13,000 \text{ uF}$ in the same package. This scaling rule allows you to readily answer the age-old question: “Say, what if I were to use two 250V caps in series instead of two 500V rated caps of the same physical size in parallel? Will I get more or less capacitance?” Here we figure $C_{250} = C_{500} (500/250)^{1.5} = 2.82 C_{500} <$

Category	Snap-in Capacitor	Plug-in Capacitor	Screw-terminal Capacitor
Application power range	0.1 - 30 kW	0.5 - 50 kW	0.5 kW - 10 MW
Mechanical Integrity	Moderate	Excellent	Excellent
Mounting scheme	Circuit board	Circuit board	Circuit board or bus assembly
Cost of Assembly	Low	Moderate	High
Ability to re-work	Poor	Moderate	Superior
Ability to heatsink	Poor	Poor	Superior
Ripple current per cap	< 50 A	< 50 A	< 100 A
Max Temperature	105 °C	105 °C	105 °C
Voltage Range	6.3 - 500	6.3 - 500	6.3 - 550
Size Range	22x25 to 50x105	35x40 to 50x143	35x40 to 90x220
Best Typical Life at 85 °C	90k hours	> 100k	> 100k
Overvoltage withstand	Moderate	Moderate	Superior
Series Inductance	Low (10-40 nH)	Moderate (20-40 nH)	Moderate (25-80 nH)

Table 1: Comparison of three main capacitor types used in power inverters: Snap-in capacitors, plug-in capacitors, and screw-terminal capacitors .

$4C_{500}$ so we realize that using the higher-voltage caps is better when high capacitance is needed. Also, just inspecting the conserved quantity $CV^{1.5}$ tells us that charge storage per capacitor volume ($Q=CV$) is maximized at low voltage ratings and that energy storage ($E=\frac{1}{2}CV^2$) is maximized at high voltage ratings. From a physical standpoint, these facts make sense: Charge storage ability is related to dielectric surface area while energy storage is related to dielectric volume. The aluminum oxide is grown upon the aluminum foil in proportion to the anodization potential in the relationship 1.4 nm/V. Therefore the etch pores must be larger for high-voltage foil so that etched surface area decreases; but the oxide is thicker so that dielectric volume increases. In fact, some high voltage foils are over 1/3 dielectric by weight.

ESR and ripple current versus voltage rating

Now even though the highest capacitance density for a given bus voltage is realized with the highest capacitor voltage ratings, you might wonder about the ripple current rating. One might guess that since the highest-voltage capacitor market has grown immensely over the past 20 years at the expense of the low-voltage capacitors, that high-voltage capacitors must offer some advantages to stringing lower-voltage capacitors in series. In general, higher-voltage capacitors use higher-resistivity electrolyte and denser papers, so their ESR is much higher. On the other hand, ripple rating varies only weakly with the ESR, inversely as the square root of the ESR. It turns out that two 550V caps of a given

size in parallel will handle about the same or a little more ripple than two 300V or even two 250V caps of the same size in series. And two 400V caps in parallel handily beat two 200V caps in series.

Since the inverter market has grown and the bus voltages are greater than 150 volts, the market for high-voltage aluminum electrolytic capacitors has kept pace and reflected the shift in the power supply topology. One thing to keep in mind is that the high-voltage caps are a little more expensive, but save on component count and complexity, and one needn't worry about voltage division between series legs. Also, when caps are used in series, additional voltage derating is recommended.

Mechanisms limiting capacitor life

Now even though these capacitors have ratings of 85 °C or 105 °C ambient with ripple, the capacitor life ratings are generally only a few thousand to perhaps 15,000 hours at these ratings. There are 8,760 hours in a year, so these capacitors will not last many years under full-load ratings. These full-load ratings are specified as accelerated life test ratings. Many deleterious chemical and electrochemical reactions in the capacitor system are accelerated with temperature. For example, electrolyte vapor pressure drives out the electrolyte through the polymer seals. Leakage current generates hydrogen gas which increases the ESR (effective series resistance). The electrolyte components decompose. Water in the electrolyte is consumed. The dielectric becomes more conductive. It turns out that most of these effects have a similar activation energy, E_a , discussed

below, which leads to the rate of their corresponding effects doubling every 10 °C.

Quantifying life-limiting degradation rates

The effect of temperature on the degradation rate for aluminum electrolytic capacitors is based on the Arrhenius rate of chemical reaction of aluminum oxide (alumina). The activation energy E_a for a material is the average energy required to excite an electron of that material from its quantum potential well. For anodic alumina the value is given in the literature as $E_a = 0.94$ eV. The Boltzmann constant $k = 8.62 \times 10^{-5}$ eV/K, so we have $E_a/k = 1.091 \times 10^4$ K. The Arrhenius equation is:

$$T_F = e^{\frac{E_a}{k} \left(\frac{1}{T_2} - \frac{1}{T_1} \right)} \quad (3)$$

Deriving the “life doubles every 10 °C” rule

The Arrhenius equation for the temperature life factor T_F may be rearranged as follows to establish the familiar “doubles every 10 °C” rule:

$$T_F = e^{\frac{E_a}{k} \left(\frac{1}{T_2} - \frac{1}{T_1} \right)} = e^{\frac{E_a}{k} \frac{T_1 - T_2}{T_1 T_2}} \quad (4)$$

If we define $\Delta T = T_1 - T_2$ and choose $T_1 T_2$ based on the normally highest usage electrolytic core temperature range of 125 °C this evaluates to:

$$T_F = e^{\frac{1.091 \times 10^5}{(398 \text{ K})^2} \left(\frac{\Delta T}{10} \right)} = e^{\ln 2 \times \Delta T / 10} = 2^{\Delta T / 10} \quad (5)$$

which is an approximation often used in the capacitor industry. At lower temperatures, this approximation is

conservative, as the original Arrhenius equation would predict that the temperature life factor would double every 7-9 °C.

The meaning of life

This principle that capacitor life doubles every 10 °C cooler the capacitor is operated needs to be mapped to some definition of the life of a capacitor. To illustrate this point, consider a capacitor rated 5,000 hours at 85 °C with 10 amps of ripple current. Nothing magical happens suddenly at 5,001 hours on such a test. In fact, during this life test, an accelerated ageing process has already begun, and chances are that the ESR has increased and the capacitance has decreased from the initial values prior to the test. If this is not the case, then the capacitor is underrated. Life is generally defined as the time to which a certain level of parametric degradation occurs. As a practical matter, this is usually the time required for the ESR to reach double or triple its initial value or limit.

Definition of core temperature

The capacitor life equation is always based on a temperature, and this is not the ambient temperature or the case temperature, but rather the “hot-spot” core temperature. In the instance of a capacitor DC life test without ripple current, these three temperatures are all the same, assuming that the DC leakage current is causing negligible heating, which is usually true. But most capacitor applications have enough ripple current to cause the capacitor winding temperature to rise above the case

and ambient temperatures, and the hottest place in the winding, usually near the top center of the winding if we are regarding the capacitor in a terminals-up view, is dubbed the “hot-spot.” Ironically, this hot-spot is often near the coolest place of the capacitor, often the top center of the capacitor top (“header”).

Components of a capacitor life model

Capacitor life L is a strong function of core temperature. The core temperature T_c is the ambient temperature T_a plus the heat rise ΔT due to ripple current I_r .

$$T_c = T_a + \Delta T = T_a + I_r^2 R_s \theta \quad (6)$$

where R_s is the capacitor’s effective series resistance (ESR) and θ is the thermal resistance from the capacitor core to ambient. So there are three main components to modeling the capacitor life: 1. Thermal model (θ), 2. ESR model (R_s), and 3. Life Model (L).

Thermal model of aluminum electrolytic capacitors

The winding of a capacitor conducts heat effectively in the axial direction, poorly in the radial direction. The winding may be considered to be divided into layers of aluminum foil with excellent thermal conductivity, interleaved with layers of papers with conductivity over three orders of magnitude ($1,000\times$) poorer. These layers are in series in the radial direction and in parallel in the axial direction. The details of a thermal analysis of aluminum electrolytic capacitors are presented in papers available at our website. Basically the most important result is that heat is transferred most readily in

the axial direction from the hot-spot of the capacitor to the can bottom. Special construction known as “extended cathode” may be used in the capacitor winding and assembly to improve the thermal contact between the winding and the can bottom. At any rate, after the heat is transferred to the bottom of the can, it is transferred elsewhere. This is not to say that radial heat transfer effects are negligible, because they are not. A tall, thin capacitor winding may internally radiate and convect over half of the heat from the winding to the can. But in general, the heat flux (flow per area) is greatest by far at the can bottom, especially when extended cathode construction is incorporated.

In the usual environment of a capacitor in still air, the heat spreads around the can and radiates and convects from the can to the environment. In an environment with forced-convection, the heat drop from can bottom to can top may be significant. The temperature distribution of the can wall is a function of the air speed, capacitor size, can wall thickness, how full the capacitor is wound, and whether extended cathode construction is used. It is interesting to note that generally the hottest and coolest places on the capacitor are near each other—the inside top of the capacitor winding and the middle of the capacitor top (“header”).

Heatsinking capacitors

Some customers choose to use a heat sink to keep their capacitors cool to prolong the life or to run higher ripple current. The best way to heatsink a capacitor is to mount the heatsink on the bottom of the capacitor.

Cornell Dubilier capacitor construction

At Cornell Dubilier, we have been using extended cathode construction in our screw-terminal capacitors for decades. These family types are now standard, and are designated with a “C” in the family name: DCMC, 500C, 520C, 550C, and 101C.

We use “pitchless” construction, meaning there is no tar, pitch, or wax used inside of the capacitor. Our screw-terminal capacitors have a special construction that features ribs and a spike in the bottom of the can and on the underside of the header. The spikes center the winding as they are inserted into the opposite ends of the cylindrical mandrel hole that runs along the axis of the winding. The ribs run radially outward from the base of the spikes, and they grip the winding tightly on the top and bottom surfaces. These ribs also reinforce the can bottom and the header. An added feature of pitchless construction is the lack of a compound that may melt and clog the header’s safety vent. We have seen truly awesome explosions from competitors’ capacitors that fail with pitch-clogged safety vents.

We are now incorporating this extended-cathode, pitchless construction in our plug-in capacitors. These new families are designated with a “C” in the family type: 4CMC, 400C, 420C, 450C, and 401C. Notice that these plug-in family designations correspond to our screw-terminal family designations with the first letter of the screw-terminal family name replaced with a “4.” Our snap-in capacitors are among the best in the industry, but their construction is inherently not as mechani-

cally robust as our screw-terminal and plug-in capacitors. The header is thinner, and there are no spikes and ribs in the can and header to tightly secure the winding. Consequently, their performance in mechanical shock and vibration is not as good. We generally use pitchless construction in most of our snap-in capacitors, except for some 40 and 50 mm diameter units.

ESR models

Existing impedance models of aluminum electrolytic capacitors in the literature are based almost exclusively on a capacitance C with an effective lumped series resistance (ESR) and sometimes a series inductance (ESL). There are several limitations with this approach. First, the ESR (effective series resistance) of a capacitor that is most typically used in this model is the value measured on a capacitance bridge with a small-signal sinusoidal excitation. This ESR lumps together a series resistance that is actually in series with the aluminum oxide dielectric and a parallel resistance that is internal to the dielectric. Thus the ESR is not the “effective” series resistance at all when the step response (or any other non-sinusoidal response) of the capacitor is considered. In fact, the voltage drop at the capacitor terminals during a high-current transient event may be in error by more than an order of magnitude when the simple $C+ESR+ESL$ model is used.

The other limitations to using a single, fixed value of capacitance and ESR are that the temperature coefficients of capacitance and ESR are not taken into account, nor are the frequency responses. Figure 3(a)

shows a typical impedance sweep of an aluminum electrolytic capacitor over a broad range of frequencies and temperatures. Figure 3(b) shows the simple C+ESR+ESL model of this capacitor. Not only are the frequency and temperature variations of the capacitor not addressed, but the predicted capacitance and ESR are incorrect in some cases by more than an order of magnitude. Clearly, an improved model is needed whenever accurate results are desired.

At Cornell Dubilier we have recently developed very sophisticated impedance models. Figure 3(c) shows the results of a model of a particular capacitor. These models will be presented in a future publication, and we anticipate that we will have Spice models available at our website soon. For the purpose of modeling ESR

sufficient for life modeling, a simplified model is sufficient.

A simplified ESR model

It is apparent that there are several components that contribute to the ESR: the metallic resistance of the terminals, of the aluminum tabs which are welded to the foil, and of the foil itself; the resistance of the wet papers that separate the anode and cathode, and of the electrolyte that resides in the etched pits of the anode foil; and the resistance associated with the dielectric loss, or dissipation factor (DF_{OX}) of the aluminum oxide dielectric. The dependence of the electrolyte resistance on viscosity and ionic mobility as a function of temperature give rise to a strong temperature-dependence.

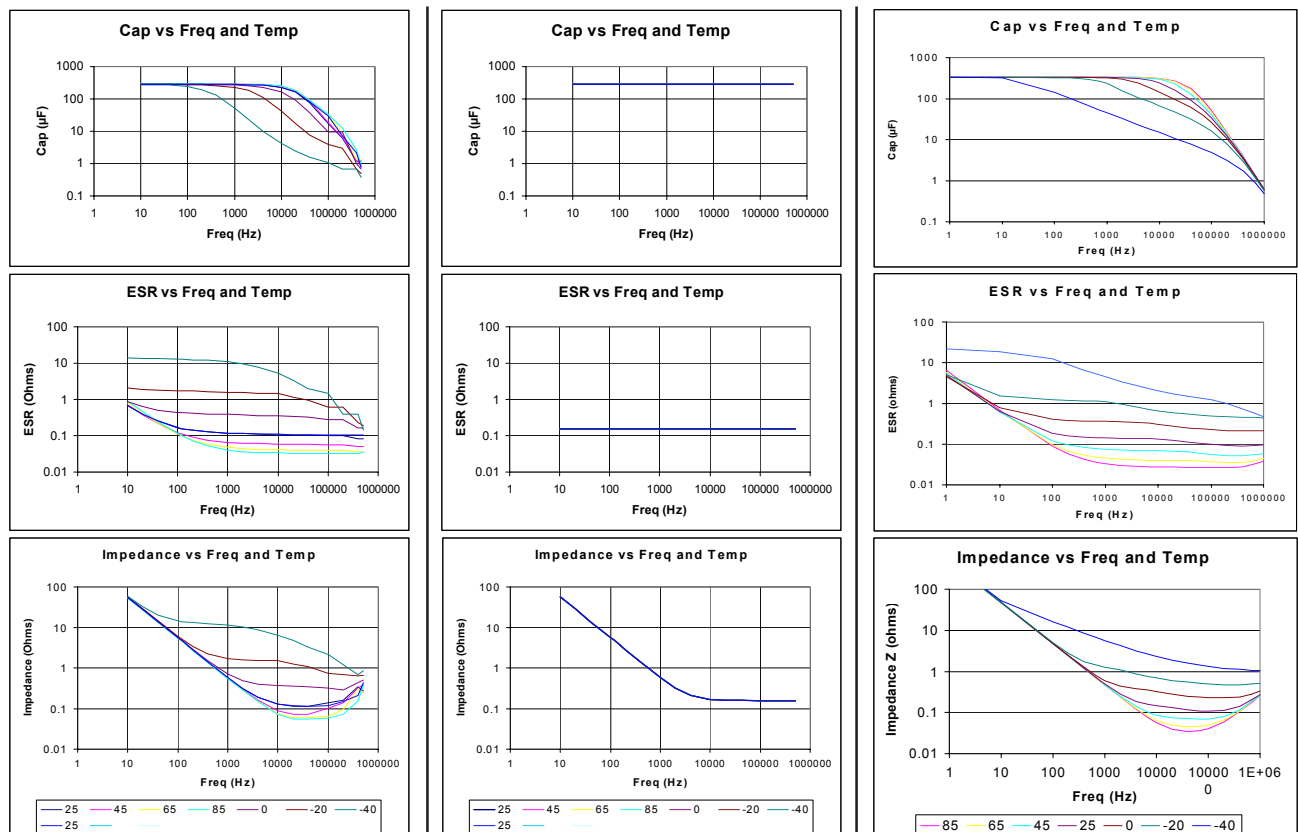


Figure 3(a, left; b, center; c, right): Actual capacitance, ESR, and impedance (left), results from present oversimplified C+ESR model(center), and results from improved model (right) .

dence of the ESR.

Basically, though there are many components of the total ESR (Rs), it may be modeled fairly accurately with a two-term equation.

$$R_s = R_o(T) + X_c \times DF_{ox} = R_o(T) + DF_{ox}/2\pi fC \quad (7)$$

The first term (Ro, “ohmic” resistance) represents the true series components outside the dielectric (terminals, tabs, foil, electrolyte, paper) as a temperature-varying quantity and the second term is a frequency-varying quantity that represents the internal dielectric loss of the aluminum oxide. The dielectric dissipation factor, DF_{ox}, is about 0.013 for Al₂O₃.

ESR variation with temperature and frequency

It is apparent that, depending on the capacitance, the second term of (7) becomes negligible compared to the first term above some frequency f_{HF} :

$$f_{HF} = 3DF_{ox}/RoC = 1/(25RoC) \quad (8)$$

The temperature variation of Ro exhibits a strong negative temperature coefficient. At 85 °C, Ro may drop by a factor to 30% of its room-temperature value.

ESR for non-sinusoidal ripple current

Ripple current in inverter applications is almost never sinusoidal. Generally there are two strong frequency components of the ripple current, a rectified mains component and an inverter switching component, plus many harmonics of these two components. The fundamental frequency f_{RM} of the rectified mains ripple current is

equal to

$$f_{RM} = f_L \times N_\phi \times N_B \quad (9)$$

where f_L is the line frequency, N_ϕ is the number of phases, and N_B is 1 for half-wave bridge rectification and 2 for full-wave bridge rectification. The fundamental frequency f_{sw} of the inverter switching component of the ripple current is equal to the switching frequency. Since the ESR varies with frequency, the precise power loss would be calculated as the sum of the power losses at each frequency. But since this is cumbersome, a shortcut approximation is often used. Generally it is acceptable to lump the total RMS current into two components, one at f_{RM} and the other at f_{sw} .

Cornell Dubilier’s life model

To model the life L we use the following equation.

$$L = L_b \times M_v \times 2^{((T_b - T_c)/10)} \quad (10)$$

Here, L_b is the base life at an elevated core temperature T_b . M_v is a voltage multiplier, usually equal to unity at the full rated DC voltage, and greater than one at lower DC voltage bias. One complication arises because the electrolyte resistance Ro is a function of the actual core temperature T_c , the core temperature is a function of the power loss, and the power loss is a function of Ro, snarling us in an interdependent circle that simple algebra cannot unentangle. Our approach to solving this challenge is to use an iterative loop in a Java applet that models the core temperature and the life.

The voltage multiplier M_v

The voltage multiplier M_v is used to account for the longer life that is experienced when a capacitor is operated under derated DC voltage conditions. Capacitor life is a strong function of temperature, as we have shown, but life is generally not a strong function of voltage, at least not over a large voltage span. In larger capacitors that are very well sealed, such as our plug-in capacitors, operating at the full rated DC voltage causes hydrogen to be generated and trapped inside the capacitor. Much of this trapped hydrogen remains dissolved in the electrolyte, causing the ESR and core temperature (when ripple is present) to increase. For this reason, we assign a larger derating factor when both voltage and **absolute** core temperature are within 10% of the maximum ratings for our plug-in capacitors, types 400C, 401C, 420C, 450C and 4CMC. For our capacitors, at present we use

$$M_v = 4.3 - 3.3 Va/V_r \quad (11)$$

where V_a is the applied DC voltage and V_r is the rated DC voltage. For the plug-in capacitors only, we use

$$M_v = 0.5 (Va/Vr)^{-9.3} - 1000(Tc/Tb-0.9)^{1.65}(Va/Vr-0.9)^{1.65}, \\ Va/Vr > 0.9 \text{ and } Tc/Tb > 0.9 \text{ (plug-in's only)} \quad (12)$$

Note that T_c and T_b must be expressed as absolute temperatures (for example, Kelvin or Rankin). Figure 4 to the right shows the linear M_v for all of our capacitors along with the family of M_v curves for the plug-in capacitors at high stress levels.

Core temperature and ESR stability

The preceding section alluded to the fact that ESR changes over the life of the capacitor when hydrogen is trapped in the electrolyte. In reality, this is only one of several mechanisms that lead to instability of the ESR over the life of the capacitor. The capacitor ESR generally climbs slowly and usually linearly over the capacitor life until very high temperatures are reached. This effect basically amplifies the initial core temperature rise above ambient. Our life-modeling applets take this effect into account by increasing the initial heat rise by a factor based on average ESR changes observed from life testing we have performed.

A heuristic exercise

Now that we have discussed the basic elements of our life-modeling Java applets, you should have a better understanding of how they work and perhaps a little more confidence in their results.

Let's walk through a couple of examples of actual

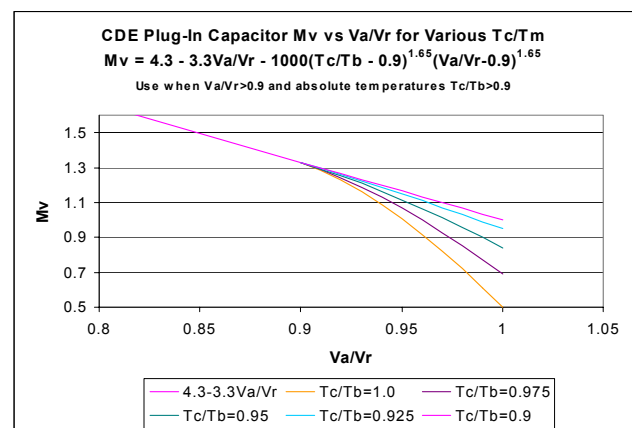


Figure 4: CDE life equation voltage multiplier M_v . The top, linear curve is common for all CDE capacitor types, and the lower curves are unique to plug-in types at the highest stress levels.

applets in action. The latest applets are available at our website. Let us suppose that we have a 50 horsepower motor drive application and need a bus capacitor bank to drive this motor. Suppose we have performed some design work and done some Spice modeling. The input power will be 480 VAC 3-phase, 60 Hz. Using 3-phase, full-wave bridge rectification, we know the nominal DC bus voltage will be 680 VDC with a 10% high-line of 750 VDC. We expect a capacitor charge waveform duty to be at least 10%. Assuming a conversion efficiency of 85%, we have

$$I_{dc} = P/EV_{dc} = 64.5 \text{ A}_{dc} \quad (13)$$

and

$$I_r = I_{dc} \times \sqrt{(1-d)/d} = 37.3\text{kW}/0.85/680\text{V} \times 3 = 194 \text{ Arms} \quad (14)$$

This system will use regenerative braking that will tend to charge the bus. We want to use a bank of capacitors rated 900 VDC and want to prevent the bus from charging the bank above 880 VDC. We would like for the bus capacitors to be able to absorb at least 4 kJ when charging from the nominal DC voltage to the maximum 880 VDC. Therefore we have

$$C > 2E / (V_2^2 - V_1^2) = 26 \text{ mF} \quad (15)$$

We also want the bus droop to be less than 80 VDC during a 40 ms power loss. From charge conservation we have

$$C > I_{dc}\Delta t/\Delta V = 32 \text{ mF} \quad (16)$$

Now we could consider our ripple of 194 Arms to be half at 360 Hz (due to the 3-phase rectified mains) and half at our 5 kHz switching frequency, so $\frac{1}{2}194\sqrt{2} = 137$ Arms. Our ambient temperature in the vicinity of the capacitors will be at most 65 °C and we want a typical life of at least 60,000 hours operating.

Java applets in action

Looking at the screw-terminal capacitors listed at Cornell Dubilier's website, we first consider large DCMC capacitors rated 450 VDC. We will use 2 series legs, and we will need at least 64 mF per leg to meet the minimum capacitance requirements. If we want a minimum number of capacitors, we could consider using 6 of the DCMC123T450FG2D (12,000 uF nominal per capacitor) per leg, for a total of 12 caps per bank. This means each capacitor will see 23 A at 360 Hz and at 5 kHz. Bringing up the screw terminal life-modeling Java applet (double applet) at our website, we choose the type DCMC, diameter 3.5, length 8.625, and voltage 450 VDC. We click Search Catalog to look up the capacitance and typical ESR automatically from our web database. We enter an applied voltage of 350 VDC and we enter the ripple currents, ripple frequencies, and ambient temperature of 65 °C. We click Calculate and we get our power dissipation, ESR's at each frequency at the calculated core temperature. We also get an estimate of typical life of only 23,700 hours. See Figure 5 on the next page. We click the double right-arrow to copy from the left panel to the right panel to avoid having to enter all the application information

again. We select type 500C, then click Search Catalog, then Calculate. We obtain about double the life, but still a bit less than what we want. Also notice that the capacitance is a bit less for the type 500C due to its higher temperature rating.

Next we consider using 7 capacitors per series bus leg (14 total). This reduces our ripples from 23A to 19A at each frequency. We enter 19 for the two currents in the right panel for the 500C, then click Calculate. This gives us 62,900 hours, barely meeting our life goal. As our goal is 60,000 hours minimum typical life, and we realize that there is no conservatism in the applet, we decide to investigate the next level of performance in a type 520C. We click the double left-arrow, select a type 520C, click Search Catalog, and note that the 520C offers the same capacitance as the 500C, 11 mF. At 19 A (7 caps per leg), we obtain a very large life of 175 khrs,

and we decide that this is overkill, so we decide to be a little skimpy on the capacitance and we reconsider 6 caps per leg at 23 A per capacitor at each frequency.

This gives us a life prediction of 139 khrs, greatly sufficient for our purposes. See Figure 6 on the next page.

If we are satisfied with this estimate, we may click the Printable Form button below the applets to generate a text-based page that may be printed, saved as an html file, or cut and paste into an e-mail application.

In this particular example, it's the 65 °C ambient that is forcing us to use a higher-grade 520C capacitor. Were the ambient 55 °C, the type 500C would be perfect for the application. One thing to keep in mind, if you need a little more capacitance or ripple capability, give us a call or send us an e-mail and we can probably work up a design to provide the best value for your application.

The applets may be used to examine the effects of air-

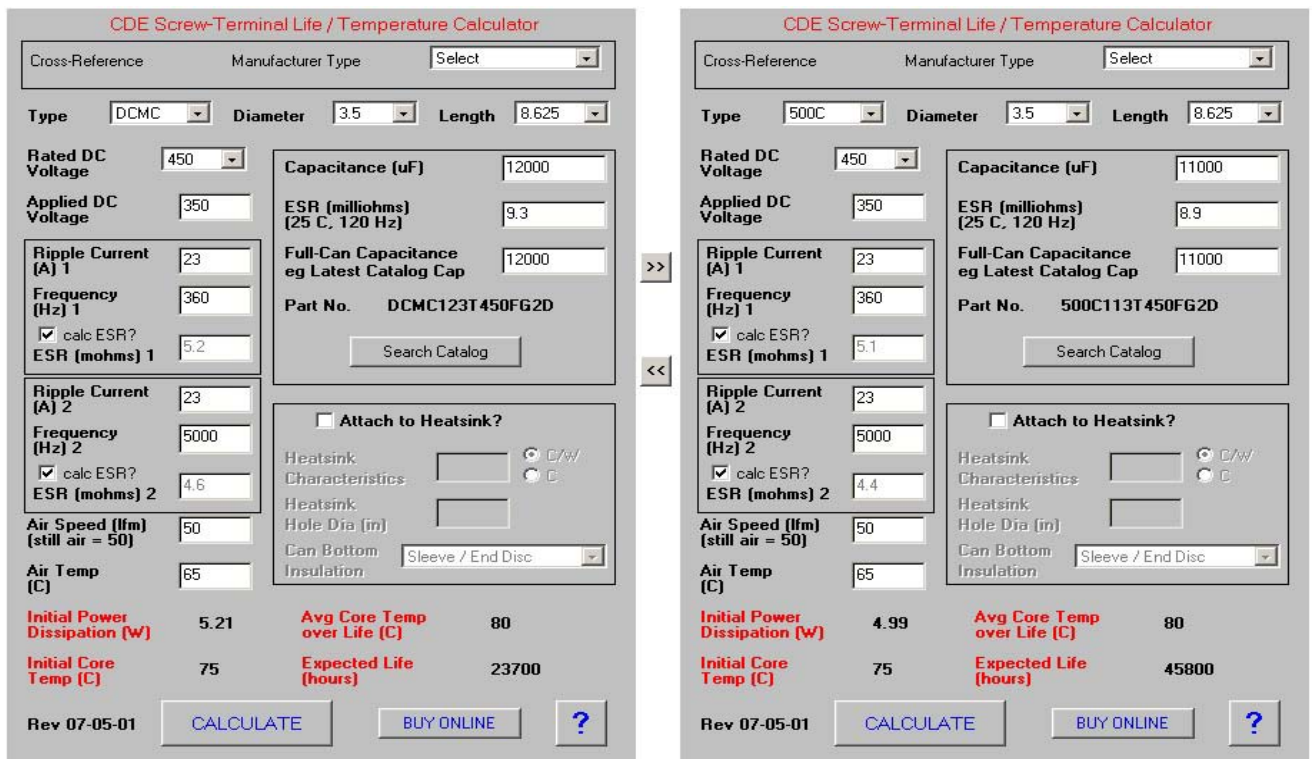


Figure 5: Cornell Dubilier's life-modeling Java applet output for an example 50 HP inverter capacitor application. The DCMC and 500C do not meet the required target life requirements of 60,000 hours in this application.

flow, ambient temperature, ripple current magnitude and frequency, various heatsinking schemes. We have generated some interesting graphs from these life predictions. Figure 7a shows the effect of ripple current and air velocity on a typical large high voltage capacitor. In applications with high ripple current, some customers have asked us about the trade-off between forced airflow and ambient temperature on capacitor life. Figure 7b shows curves of constant life for airflow vs ambient temperature for a typical large high-voltage

capacitor. This graph demonstrates that while providing airflow helps cool a capacitor, lowering the ambient temperature makes a dramatic difference. Fortunately, often when airflow is increased, the ambient temperature in the vicinity of the capacitors decreases due to mass transfer effects.

Figure 7c shows the effect of ripple frequency and ripple current for a large type 550C high-voltage capacitor at 55 °C ambient.

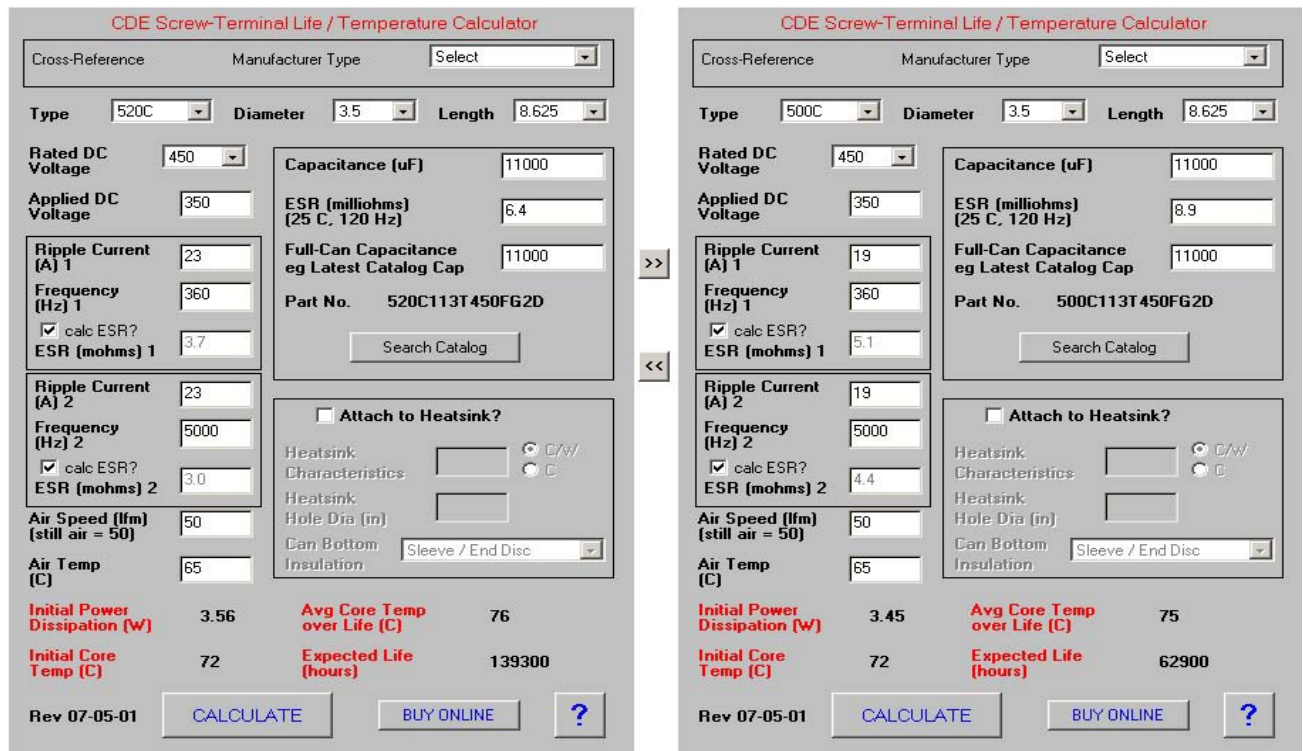


Figure 6: Cornell Dubilier's life-modeling Java applet output for an example 50 HP inverter capacitor application. The 500C and 520C meet the required target life requirements of 60,000 hours in this application.

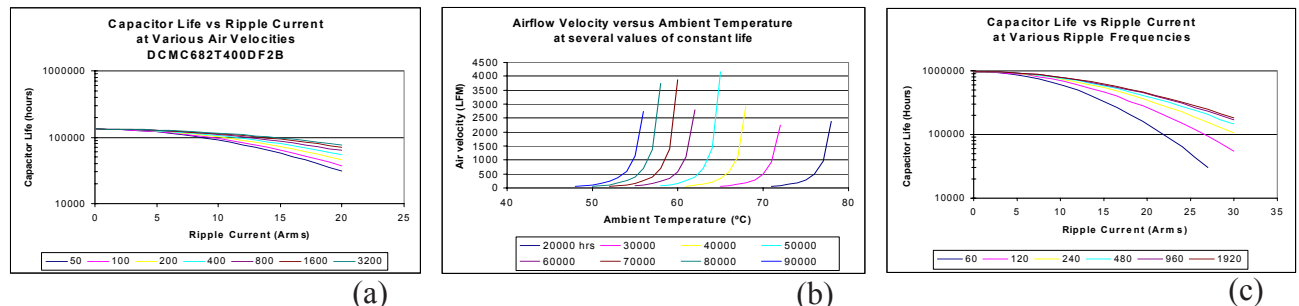


Figure 7: Graphs of the effects of various parameters on capacitor life.