Electrolytic Capacitor Lifetime Estimation

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Introduction

Aluminum Electrolytic Capacitors ("alu-elcaps", "elcaps") are essential for the function of many electronic devices. Ever increasing demand for enhanced efficiency, the expanding utilization of renewable energy and the continuous growth of electronic content in automotive applications have driven the usage of these components.

In many applications, the lifetime of electronic devices is directly linked to the lifetime of the elcaps inside [9]. To ensure reliable operation of electronic devices for a defined period, a thorough knowledge of the vital properties of elcaps is mandatory.

The present article outlines the construction of elcaps and explains related terms like ESR, ripple current, self-heating, chemical stability, and lifetime. Two estimation tools for obtaining elcap lifetime approximations in an application are introduced and illustrated by an example.

Construction of Elcaps

Aluminum electrolytic capacitors combine voltage proof capabilities starting at a few Volts up to approx. 700V and a wide capacitance range from 1 µF extending beyond 1 F while being very compact in size. A highly roughened anode foil is covered by a thin dielectric layer and the complete surface area is contacted by an exact-fitting cathode, the electrolyte liquid (Fig. 1).

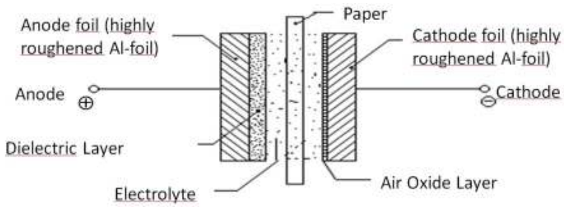

Fig. 1: Internal construction of an Elcap

The liquid electrolyte is making the construction of electrolytic capacitors special and its existence yields some technical consequences.

- The flow of electrical current through the electrolyte is mediated by the movement of ions. An increase of the electrolyte temperature thus decreases its viscosity and in turn lowers the electrical resistance (ESR).

- The boiling point of the electrolyte determines the upper category temperature and limits the maximum permissible self-heating caused by the ripple current in conjunction with the ambient temperature.

- Electrolyte loss caused by electrochemical reactions at the dielectric layer (self-healing) and diffusion through the seal (drying out) lead to a drift of the electrical parameters of the elcap and to a finite lifetime.

Equivalent Series Resistance ESR

The ESR-Value (Equivalent Series Resistance) allows for an easy calculation of the thermal losses that occur during the operation of elcaps when a ripple voltage superimposes a d.c. offset voltage [1]. The equivalent series inductance ESL and the resistance $R_{Leakage}$ (in parallel with the ideal capacitor C) are not further explored in this paper.

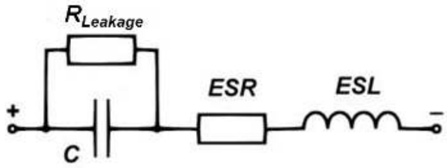

Fig. 2: Equivalent circuit of an elcap

The ESR (Fig. 2) is the sum an approximately constant, a frequency dependent and a temperature dependent part [2]:

$$ESR = R_o + R_d + R_e$$

1. Approximately constant ohmic resistance of foil, connecting tabs and solder terminals

   $R_o \cong const.$ typical values of R_o: some 10 mΩ.

2. Frequency dependent resistance of the dielectric layer (Fig. 3 (a))

   $$R_d(f) = \frac{D_{ox}}{2 \cdot \pi \cdot f \cdot C}$$

   where D_{ox} Dissipation factor of the dielectric layer
   f Frequency
   C Capacitance of the elcap

   The frequency dependency results from dielectric losses caused by the alignment of small dipoles within the oxide layer when voltage is applied [3]. This portion of the ESR has bigger impact on elcaps with a higher rated voltage, because of the thicker oxide layer (approx. 1.4 nm/V). Typical values of the dissipation factor are $D_{ox} = 0.06 \ldots 0.1$.

3. The temperature dependent resistance of the electrolyte solution in combination with the spacer paper (Fig. 3 (b)) can be estimated based on a known value at room temperature $R_e(25°C)$ by [3]:

   $$R_e(T) = R_e(25°C) \cdot 2^{-\left[\frac{T-25}{A}\right]^B}$$

   The resistance of the system made up of electrolyte and spacer paper is about 10 times higher than the resistance of the electrolyte solution itself. The (non-conducting) paper replaces part of the volume previously occupied by the (conducting) electrolyte and thus the combination of both has a lower conductivity. Typical values for elcaps with ethylene glycole-based electrolytes are $A = 40$ and $B = 0.6$ [3].

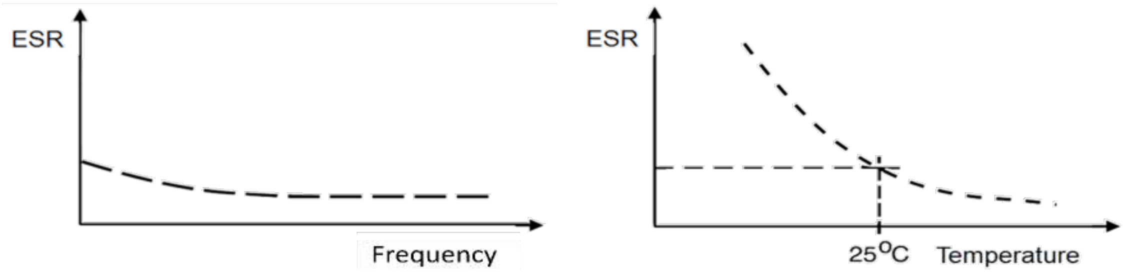

Fig. 3(a): ESR vs. Frequency **Fig. 3(b): ESR vs. Temperature**

In order to allow for an easy application of the ESR-values that show frequency, temperature and even time-dependency, Jianghai specifies maximum ESR-values in addition to the typical ESR-values. To obtain reliable and rugged designs, these maximum ESR-values should be used when selecting components.

Ripple current

In most applications, an a.c. or ripple voltage exists on top of a d.c. voltage and causes a ripple current and a self-heating of the elcap. We will consider the RMS (root mean square) value of the rated ripple currents, because currents of any frequency contribute to the self-heating [8]:

$$I_a = \sqrt{\left(\frac{I_{f1}}{F_{f1}}\right)^2 + \left(\frac{I_{f2}}{F_{f2}}\right)^2 + \cdots + \left(\frac{I_{fn}}{F_{fn}}\right)^2}$$

I_a	RMS value of the rated ripple currents
I_{f1} ... I_{fn}	RMS Values of ripple currents at frequencies *f1...fn*
F_{f1}... F_{fn}	correction factor for the current at frequencies *f1...fn*
$F_{fi} = \sqrt{\frac{ESR(f_0)}{ESR(f_i)}}$	where f_0= reference frequency of the nominal ripple current

The correction factors for the various frequencies originate from the frequency dependency of ESR. For greater ease of use, correction factors for the currents at certain frequencies are tabulated in the datasheets rather than ESR ratios at different frequencies. As ESR vs. Frequency behavior depends also on the rated voltage, many datasheets show tables of correction factors for distinct voltage ranges.

Self-heating of elcaps during operation

During operation, the elcap temperature rises above ambient. The core temperature inside the elcap exceeds the temperature at the elcap surface and in the steady state the applied electrical power P_{el} matches the heat power P_{th} dissipated to the ambient.

$$P_{el} = P_{th}$$

The main cooling mechanisms for elcaps are heat radiation and (free or forced) convection (Fig. 4). With large can sizes, the cooling by heat radiation is typically more effective than the cooling effect achieved by convection (forced cooling can be used to increase the effect of convection).

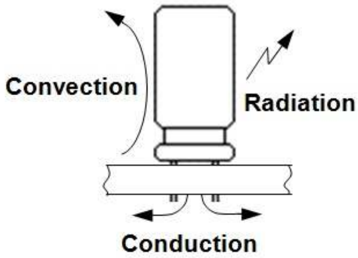

Fig. 4: Cooling mechanisms of elcaps

The capability to radiate heat in the infrared spectral band depends on the material properties of the elcap surface area A: related to a black body, an elcap can covered with an isolating sleeve has a radiation coefficient (emissivity) of $\varepsilon = 0.85$, while a blank elcap surface merely has a radiation coefficient of $\varepsilon = 0.4$ [5]. The sleeve color in the visible wavelength range (approx. 400 ~ 700 nm) does not matter.

Heat radiation is governed by Stefan-Boltzmann‘s law:

$$\begin{aligned} P_{rad} &= \varepsilon\sigma A(T_s^4 - T_a^4) \\ &= h_{rad} \cdot A \cdot \Delta T \end{aligned}$$

where:	$\varepsilon \cong 0{,}85$	emissivity
	$\sigma = 5{,}67 \cdot 10^{-8} \frac{W}{m^2K^4}$	Stefan-Boltzmann‘s constant
	A	elcap surface area (w/o seal)
	$h_{rad} = \varepsilon\sigma(T_s + T_a)(T_s^2 + T_a^2)$	heat transfer coefficient radiation
	T_s	surface temperature elcap
	T_a	ambient temperature
	$\Delta T = T_s - T_a$	temperature rise

For free convection we have:

$$P_{conv} = h_{free} \cdot A \cdot \Delta T$$

where	$h_{free} = 1{,}32 \cdot \left[\frac{\Delta T}{D}\right]^{1/4}$	heat transfer coefficient convection
	D	elcap diameter

For free convection in conjunction with the heat radiation, the following numerical values of total heat transfer coefficients are typically observed:

$$h_{tot} = h_{free} + h_{rad} \cong 13{,}5 \sim 17 \frac{W}{m^2K}$$

In case of forced air cooling with air velocity v (in m/s), the total heat transfer coefficient can be approximated by [5]:

$$h_{tot} \cong 5 + 17 \cdot [v + 0{,}1]^{0{,}66}$$

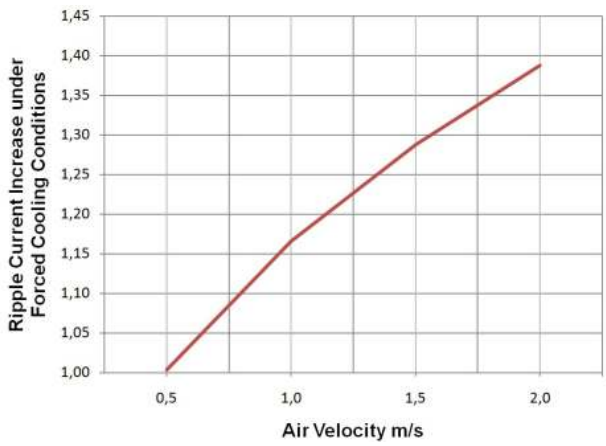

Fig. 5: Increase of permissible ripple current load by forced convection

By the application of forced cooling with air velocity v = 1 ~ 2 m/s, the contribution of convection to the total cooling effect can be significantly improved compared to free convection ($v \lesssim 0{,}5\ m/s$) (Fig. 5).

Heat conduction only applies for very small, axial elcaps, and when liquid cooling is utilized. The individual equivalent thermal resistances of each cooling mechanism may be lumped together into a single overall thermal resistance R_{th}. The temperature rise ΔT of an elcap with surface area A when applying a ripple current I is:

$$\Delta T = I^2 \cdot ESR \cdot R_{th}$$

Where $$R_{th} = \frac{1}{h_{tot} \cdot A}$$

The next step to obtain more insight into the thermal properties of elcaps is the evaluation of the core temperature, because this is the most important parameter for the lifetime estimation of elcaps. The core temperature T_c can be estimated by

$$T_c = \Delta T \cdot \frac{R_{th}^{inside}}{R_{th}} + T_s$$

where the combined thermal resistances in axial and in radial direction numerically range in the order of $R_{th}^{inside} \cong 1 \sim 3\,\frac{K}{W}$.

In practice, the measurement of the surface temperature at the can bottom provides a good approximation of the core temperature value for radial and small snap-in elcaps with can sizes up to 25 mm in diameter. For larger can sizes, a direct measurement of the core temperature by means of a thermocouple is recommended. Jianghai supplies elcaps with pre-mounted thermocouple for evaluation purposes on request.

Chemical Stability

Modern electrolyte systems are multi-compound mixtures, and their chemical stability during the lifetime of an elcap is a must. A good indicator to assess the chemical stability is the "shelf life" (Table 1, right column). As opposed to the regular storage of elcaps at moderate temperatures, the shelf life test is a demanding accelerated life test that subjects the test specimens for a pre-defined period to their upper category temperature without any voltage applied. Without any voltage applied, the elcap cannot benefit from any self-healing during the test – this particular feature makes the shelf life test quite tough. Vital parameters like leakage current, capacitance, and dissipation factor must stay within predefined limits after the test. A high numerical value of the shelf life is a good indicator for chemical stability, high purity of the materials and an advanced production quality. The results of this test are documented on the datasheets of all Jianghai series.

Reliability and lifetime

Reliability and lifetime are answers to the questions of "How many elcaps may fail during the usage of my application?" and "How long will the elcaps survive in my application?" Yet these two questions are different, they are related to each other.

The typical time course of reliability density for elcaps follows the so-called "bathtub curve" [6]. The failure rate ("FIT rate") λ designates the number of failures per unit time (failure density, measurement unit FIT = "Failures in Time" in $\frac{10^{-9} failures}{h}$).

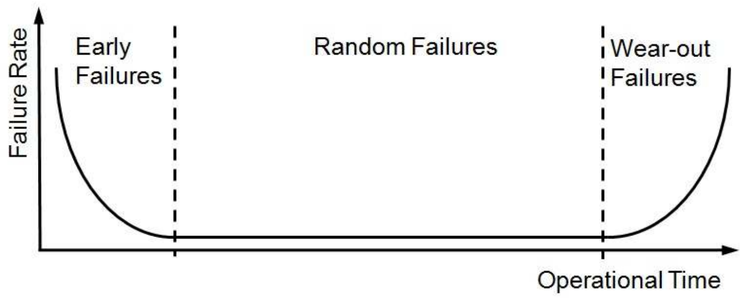

Fig. 6: FIT rate vs. time

The bathtub curve in Fig. 6 shows three distinct consecutive segments:

1. The early failure period ("infant mortality") with a decaying FIT rate λ
2. The period within the normal lifetime has a constant FIT rate λ that describes the occurrence of random failures
3. The final segment with increasing FIT rates λ that originate from wear-out and changes beyond acceptable limits at the end or after the end of the regular lifetime

In the production process of elcaps all products are subject to forming in the factory – this process step is similar to a "burn-in". Early failures in the application are thus a rare exemption [1].

For the further proceeding we consider that the elcap is operated during the random failure period of the bathtub curve and that the operating conditions are "valid" within the limits of the specification. “Valid operating conditions” are defined by a permissible combination of voltage, polarity, ambient temperature, ripple current, mechanical stress and a “clean” environment (absence of chemically aggressive agents in the vicinity of the elcap).

The end of the lifetime is reached when certain parameters exceed pre-defined threshold values. It is common practice to allow a certain portion of species to be outside of the limits. A deviation of certain parameters from pre-defined ranges does not mean a total loss of the elcap function, but the design of the application should be done in a way to allow it to function even under these unfavorable conditions.

There exist several definitions and terms that are used to describe elcap lifetime:

1. **Endurance**
   The method for conducting an endurance test is described in the IEC60384-4 standard: the elcaps are operated at their rated voltage and at their upper category temperature and the time course of their electrical parameters (capacitance, ESR, leakage current) is observed until certain thresholds are hit. Depending on the number of types under test, up to almost 7% of the tested items are allowed to be out of a predefined range at the end of the test.

2. **Useful life**
   The term useful life relates to a German preface of the (meanwhile withdrawn) standard DIN IEC 60384-4 [1]. The test procedure comes close to the actual operating conditions in the application: in addition to the d.c. voltage and the presence of the upper category temperature, a ripple voltage is superimposed that causes additional thermal stress by self-heating.

When comparing databooks of different elcap manufacturers, an inconsistent use of the above terms becomes obvious. The meanings of the terms are frequently mixed and redefined. The range of terminology comprises terms like „load life”, “useful life”, “endurance”, “life expectancy”, “operational life”, and “service life”. In addition to different limits that define the end of the lifetime, some manufacturers even use differing standards to allow for a certain amount of test items to be out of the specified range – this makes a comparison of the various lifetime values between different suppliers even more difficult.

Today, there exist no valid uniform standards that could be used to obtain an exact definition of the terms and their meaning. A U.S. standardization committee has worked out a proposal towards the unification of test conditions, published as EIA IS-749 („Rectified Mains Application Expected Wear-Out Lifetime Test“) for the lifetime testing of elcaps located behind the mains rectifier [4].

Until generally applicable standards are released and implemented, Jianghai resolves to publish all relevant definitions and test conditions in the datasheet (Table 1).

	Useful Life		Load Life	Endurance Test	Shelf Life
Lifetime	**7000h**	>200000h	5000h	5000h	1000h
Leakage Current	Not more than specified value		Not more than specified value	Not more than specified value	Not more than specified value
Capacity Change	Within ± 30% of initial value		Within ± 20% of initial value	Within ± 20% of initial value	Within ± 20% of initial value
Dissipation Factor	Not more than 300% of specified value		Not more than 200% of specified value	Not more than 130% of specified value	Not more than 200% of specified value
Condition: **Applied Voltage** **Applied Current** **Applied Temperature** **Failure Rate Level**	U_R I_R 105°C ≤ 1% Failure Rate	U_R 1,6 x I_R 40°C ≤ 1% Failure Rate	U_R I_R 105°C guaranteed	U_R $I_R = 0$ 105°C	$U_R = 0$ $I_R = 0$ 105°C After test: U_R to be applied for 30min >24h before measurement

Table 1: Full definition of test conditions and allowed ranges

In addition to the more marketing oriented „useful life“ figure, Jianghai also publishes well-defined specifications of „load life“ and „endurance“ to increase the transparency for the end user. Shelf life test results are provided to give an indication of the chemical stability of the elcaps and thus the reader of the datasheet gets a full picture of the elcap series features.

Elcap lifetime diagram and lifetime model

To provide the users of their products with some tools for the lifetime estimation of elcaps, Jianghai has devised lifetime diagrams and a lifetime model. While the lifetime diagrams consider the most important parameters (temperature, ripple current) and show permissible combinations of these parameters graphically, the lifetime model also takes the influence of the actual operating voltage on lifetime into account. The utilization of these two tools is possible with many applications. Special conditions (e.g., operation close to the physical temperature limits, irregular ripple current shapes, special elcap construction, …) may limit the applicability of the estimates obtained by use of these tools, though. For each application, the results obtained by any tool need to be confirmed by the supplier.

The liquid electrolyte inside the elcap is the main cause for its finite lifetime and the continuous change of its electrical parameters [7]. Electrochemical degradation, accelerated by rise in temperature and voltage, can be estimated by use of a semi-empirical lifetime model.

Jianghai lifetime diagrams have for many series been derived from the numerical lifetime model – the grey area in the diagram shows which combinations of ripple current and ambient temperatures may lead to temperatures too close to or even exceeding the boiling point of the electrolyte (Fig. 7). These load conditions may only be applied if confirmed by Jianghai.

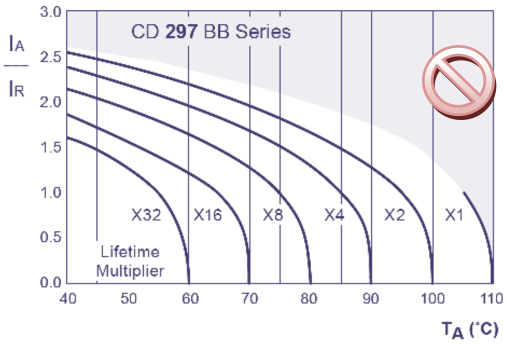

Fig. 7: Lifetime diagram for Jianghai elcap series CD_297_BB

The lifetime model provides estimates of the elcap lifetime in a given application.

The input of the lifetime model are some elcap type specific parameters from the datasheet along with some application-specific parameters like ambient temperature, ripple current load and the actually applied voltage during operation. In case of forced cooling the ripple current load capability needs to be adjusted accordingly.

Structure of the lifetime model

$$L_X = L_0 \cdot K_T \cdot K_R \cdot K_V$$

where	L_X	resulting lifetime
	L_0	lifetime at nominal ripple and upper category temperature (datasheet)
	K_T	temperature factor (ambient temperature)
	K_R	ripple current factor (self-heating)
	K_V	voltage factor (operating voltage)

Temperature factor K_T

The lifetime of elcaps follows the industry wide well established “10-Kelvin-rule” from Arrhenius: a drop of the ambient temperature by 10 K doubles the lifetime [1, 3, 4, 6, 9]. The formula for K_T reads:

$$K_T = 2^{\frac{T_0 - T_a}{10K}}$$

where	T_0	upper category temperature
	T_a	ambient temperature in the application

Ripple Current K_R

Jianghai estimates the impact of the applied ripple current on the self-heating and in turn on elcap lifetime by the following formula:

$$K_R = K_i^{A \cdot \frac{\Delta T_0}{10K}}$$

where $A = 1 - \left(\frac{I_a}{I_o}\right)^2$

and	I_a	ripple current in the application
	I_0	nominal ripple current at upper category temperature
	ΔT_0	core temperature increase of the elcap (typ. 5 K at T_0= 105 °C and 10 K at T_0= 85 °C)
	K_i	empirical safety factor, defined as

$T_0 = 105°C$:	$I > I_0$:	$K_i = 4$
	$I \leq I_0$:	$K_i = 2$
$T_0 = 85°C$:		$K_i = 2$

Voltage factor K_V

For smaller size radial elcaps, temperature dependent electrolyte loss (as modeled by the Arrhenius equation) governs the lifetime model. Hence, $K_V = 1$ holds for radial elcaps. For medium and large sizes (Snap-in and screw terminal types) the influence of actually applied voltage gains some impact on lifetime, because operating voltages below the rated voltage cause less stress to the dielectric layer. The closer the operating voltage approaches the rated voltage, the more of the electrolyte is consumed for the self-healing of small flaws within the dielectric layer. The self-healing (and thus the electrolyte consumption) is also exponentially depending on temperature. Vice versa, a lower operating voltage than rated voltage may extend the lifetime of elcaps significantly [4].

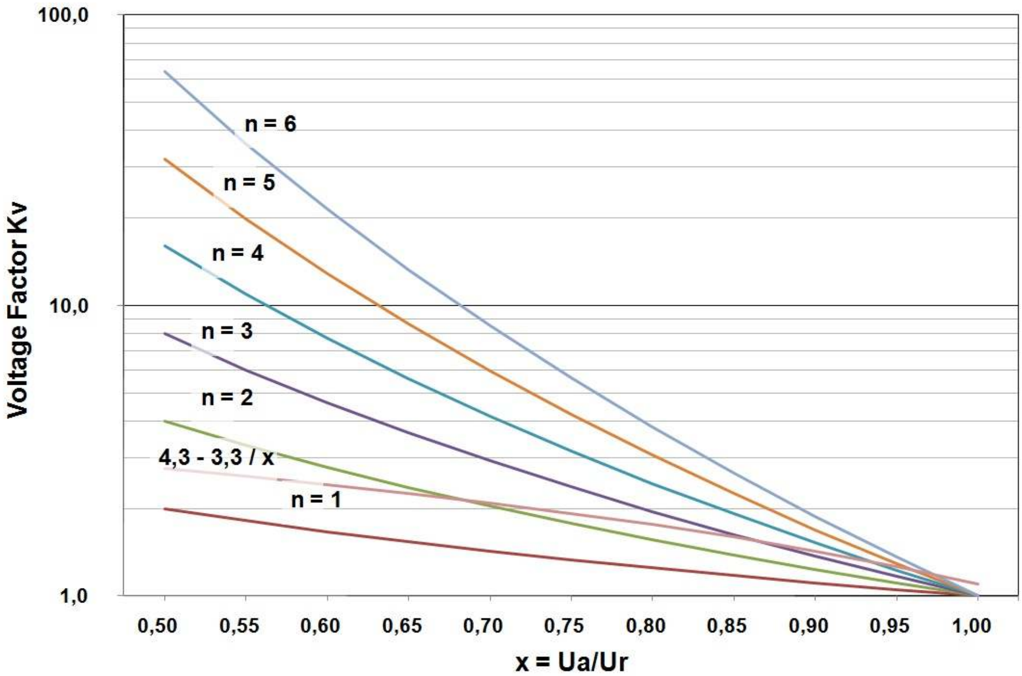

Fig. 8: Voltage factors of various suppliers [4]

Jianghai estimates the influence of the actually applied operating voltage on the lifetime of large snap-in and screw terminal elcaps by using an empirically derived formula. Operating voltages below half the rated voltage are considered impractical and are not covered by the model. Compared to the results from models of other suppliers, Jianghai has intentionally chosen exponents $n = 5$ and $n = 3$ that are offering a “moderate” position (Fig. 8).

$$K_V = \left(\frac{U_a}{U_r}\right)^{-n}$$

where U_r rated voltage

U_a actual operating voltage

n exponent, defined as:

$$0.5 \leq \frac{U_a}{U_r} < 0.8 \quad \rightarrow \quad n = 3$$

$$0.8 \leq \frac{U_a}{U_r} \leq 1 \quad \rightarrow \quad n = 5$$

Example of a lifetime estimation

The following example is supposed to serve the illustration of a practical application of the lifetime diagram and of the lifetime model.

Let a 105 °C elcap, type 390 µF, 400 V, 35x45 mm from the snap-in series CD_297_BB from Jianghai be operated at ambient T_a = 55 °C and a ripple current of 2.51 A_{rms} at 20 kHz. The actual operating voltage equals the rated voltage of 400 V, hence only ambient temperature and ripple current load enter the lifetime estimate. The cooling is supposedly done by free convection and radiation.

The datasheet indicates a nominal ripple current of 1.27 A_{rms} at 120 Hz and 105 °C and a frequency correction factor of 1.4 for frequencies beyond 10 kHz and rated voltages 315 ~ 450 V. The lifetime („useful life“) is specified to be 7,000 h at nominal load conditions.

The ratio of the actual, frequency-rated ripple and the nominal ripple current is computed as

$$\frac{I_a}{I_0} = \frac{\frac{2{,}51 A_{rms}}{1{,}4}}{1{,}27 A_{rms}} = 1.41$$

From the lifetime diagram (Fig. 9), we obtain an approximate value for the lifetime multiplier of 16 at the intersection of ambient temperature and ripple current ratio. The estimate for the “useful life” of the elcap in this application under the mentioned operating conditions is:

$$L_x = L_0 \cdot 16 = 7{,}000\ h \cdot 16 = 112{,}000\ h \cong 13\ years$$

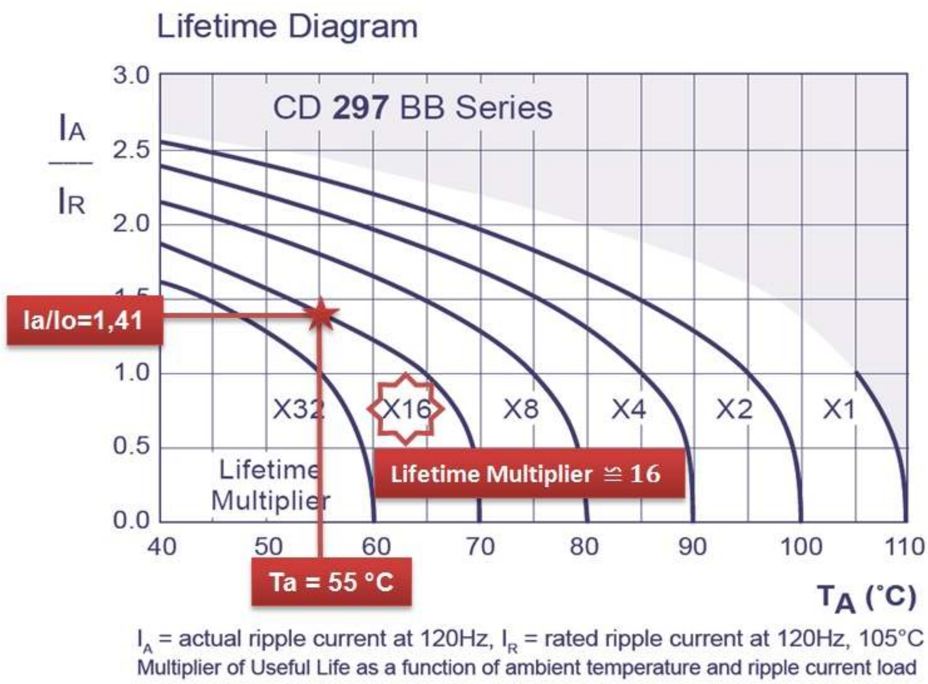

Fig. 9: The lifetime multiplier is found at the intersection of the actual operating parameters

Alternatively, the lifetime can also be estimated by using the numerical lifetime model:

$$L_X = L_0 \cdot K_T \cdot K_R \cdot K_V$$

$$= L_0 \cdot 2^{\frac{T_0 - T_a}{10K}} \cdot K_i^{\left[1-\left(\frac{I_a}{I_0}\right)^2\right] \cdot \frac{\Delta T_0}{10K}} \cdot \left(\frac{U_a}{U_r}\right)^{-n}$$

Inserting the values of

$L_0 = 7{,}000\ h$

$T_0 = 105\ °C$

$T_a = 55\ °C$

$K_i = 4$

$I_a = \frac{2.51 \mathrm{A_{rms}}}{1.4} = 1.79\ \mathrm{A_{rms}}$

$I_o = 1.27\ \mathrm{A_{rms}}$

$\Delta T_0 = 5\ K$

$U_r = U_a$: $\quad 0.8 \le \frac{U_a}{U_r} \le 1 \rightarrow n = 5$

yields

$$L_X = 7{,}000h \cdot 32 \cdot 0.5 \cdot 1$$
$$= 7{,}000\ h \cdot 16 = 112{,}000\ h \cong 13\ years$$

The result of the numerical estimate matches the result obtained from the graphical solution that utilized the lifetime diagram.

Summary

Aluminum electrolytic capacitors often determine the lifetime of electronic devices. A thorough knowledge of some of the key parameters and aging concepts of these components are necessary to ensure the reliable design of electronic devices with a predictable lifetime.

Typical electrical and thermal properties of elcaps as well as the definitions for reliability and lifetime are elucidated. Two methods are available for obtaining lifetime estimates: a graphical approach (lifetime diagram) and a numerical computation (lifetime model).

The applicability of the models and their results depend on the specific product type and the particular application. Consultations with the supplier are key to get guidance throughout the design project and to confirm any estimates.

A practical example shows how the methods presented here can be applied to obtain application specific elcap lifetime estimates.

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Company Profile

JIANGHAI EUROPE GmbH with office and warehouse in Krefeld (Germany) supports the European customers of Nantong Jianghai Capacitor Co., Ltd. (Jianghai) in Nantong, China. Jianghai has been founded in 1959 at the location of the present headquarter – about two hours by car north of Shanghai. In the early years, Jianghai developed and produced specialty chemical products (e.g., electrolyte solutions). In 1970, the production of electrolytic capacitors was launched and during the following years, low and high voltage anode foil production facilities complemented Jianghai's portfolio. Being the no. 1 producer in China, Jianghai is one of the world's largest manufacturers of snap-in and screw terminal electrolytic capacitors.

Author

Dr. Arne Albertsen was born 1965 in Eutin in the north of Germany and he studied physics with a focus on applied physics at Kiel University. Following diploma (1992) and doctoral thesis (1994), both on a subject from biophysics, he pursued an industrial career at Haase Energietechnik, a medium-sized enterprise that had specialized in landfill and renewable energy technologies. He held positions in R&D, product management, division head and assistant to the CEO before he started to work with leading manufacturers of electronic components like BCcomponents, Vishay, and KOA, in 2001. He worked in managing positions in design-in and sales and marketing for passive and active discrete components until he joined JIANGHAI EUROPE in November 2008. In his current position as manager sales and marketing, Dr. Albertsen is responsible for the support of European OEM accounts, distributors and agents.

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