Keep your distance – Voltage Proof of Electrolytic Capacitors

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Introduction

Aluminum electrolytic capacitors ("electrolytic capacitors," "e-caps") are important components in many power electronics devices today. Ever-increasing requirements for energy efficiency, expanding use of renewable energy and the growing proportion of electronics in automotive applications have driven the wide use of these components.

In many applications, service life and reliability of the device depend directly on the corresponding parameters of the electrolytic capacitors [4]. In previous publications [1], [2] the author focused on the topics of life time prediction and reliability (also touching the dependence of these quantities on the operating voltage). The present article explains the reasons for the limited voltage rating of capacitors and shows the voltage ranges that must be kept to ensure safe operation.

An important parameter when selecting an e-cap is its voltage proof, which is usually given as rated, operating, or surge, or in special cases, as transient voltage. Exceeding the voltage proof - even if this is done only for a few milliseconds - may lead to immediate failure of the capacitor or decrease its performance for the remaining lifetime. In many applications, the highest ever occurring voltage load cannot be predicted. Examples for possible causes of increased voltage stress compared to the normal operating voltage are:

- Voltage spikes due to switching transients from inductive loads
- Feedback from free-wheeling motors
- High-impedance generators with varying loads
- Unbalanced load conditions or phase connection errors or dropout of a single phase
- Connection error (error in the wiring, power supplies, e.g. at construction sites)
- (destructive) over-voltage tests, e.g. UL508C "Breakdown of Components Test"

One approach is to select the rated voltage of the capacitor such that it lies far above the expected maximum voltage in the application. However, this approach contradicts the common targets of miniaturization and cost optimization. To successfully minimize the "safety margin" without sacrificing reliability, a thorough understanding of both the properties of the circuit to be designed and the capacitors to be deployed is required. In order to characterize the properties of the circuit completely, measurements in addition to simulations are useful (“to measure” means “to know”). To illustrate the definitions and boundaries of the voltage proof capability of electrolytic capacitors, we first consider construction and manufacturing of these electronic devices.

Design and manufacture of electrolytic capacitors

Aluminum electrolytic capacitors combine voltage proofs ranging from several volts to about 750 Volts and a wide capacitance range from 1 µF to above 1 F, while offering a compact size. A highly roughened anode foil is being completely covered by a thin dielectric layer and contacted by an exact fitting cathode, the electrolyte liquid. (Fig. 1).

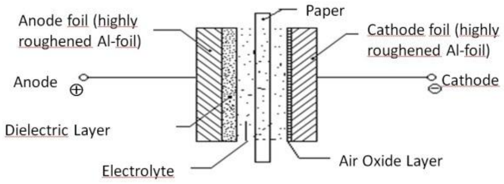

Fig. 1: Construction of an aluminum electrolytic capacitor

The manufacture process of e-caps comprises the following major production steps:

1. Etching – high purity aluminum foils of thickness 20 ~ 100 µm are the base material for the later anode- and cathode foils. The etching enlarges the total surface area of the anode material up to a factor of 140 (Fig. 2), compared to their geometric surface. Even at this early stage in the production process it is determined whether the capacitor will later be able to meet the high requirements in terms of voltage stability, reliability, long lifetime, and ripple current capability in professional industrial applications. The manufacturer has to decide at this point, whether a low product price is essential, or whether he recognizes the importance of the pore structure for the performance in the application and the product quality. The latter causes sometimes considerable extra costs in materials and processes, but it ensures a stable quality product. The pore structure of the anode material in connection with the experience of the manufacturer (and not only the forming voltage) identifies a responsible quality manufacturer.

2. Forming – the anode foil bears the dielectric layer of the e-cap and consists of aluminum-oxide (Al_2O_3). It is deposited on top of the roughened anode foil by an electrochemical process called anodic oxidation or forming. The quality of the forming, i.e. the homogeneous and complete coverage of the surface area is essential for the high reliability of the components during operation. The further the forming voltage is above the rated voltage, the smaller becomes the probability of dielectric breakdown. Typical values for the ratio of forming voltage vs. rated voltage of Jianghai electrolytics range between 1.25 (low voltage) and 1.60 (high voltage). The thickness of the dielectric layer is approximately 1.4 nm/V; this amounts to about 900 nm for an e-cap with 450 V voltage proof (this is less than 1/100 of the thickness of a human hair).

3. Slitting – the etched and formed foil comes on so-called mother rolls of about 50 cm width. By slitting, the mother rolls are cut into the widths needed for the anode and cathode material.

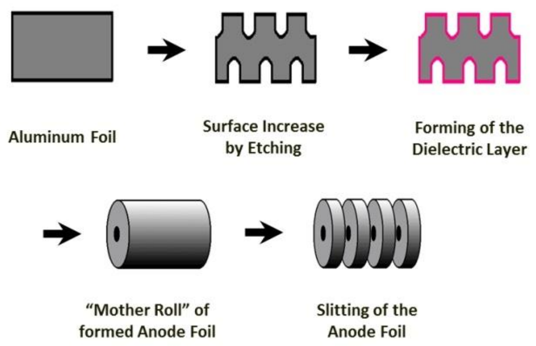

Fig. 2: Process steps for the preparation of the anode foil

4. Winding – attachment of electrical contact tabs to the foils (stitching, cold welding) and winding of anode, paper (spacer, multi-ply if needed), and cathode foil. The selection of the paper and the structures of the cathode foil have a significant influence on the subsequent performance of the component. The construction of the wound cell and the current path through the internal and external connections determine also the parasitic inductance. Although it is often desirable to protect the power semiconductors by deploying capacitors with low inductance, the capacitors may be negatively affected by brief voltage spikes themselves. It should therefore be judged case by case whether using low-inductance capacitors is reasonable.

5. Impregnation – the pores of the spacer paper in the wound cell and the complete surface area of the anode foil are covered by electrolyte, the liquid cathode.

6. Assembly of the capacitor wound cell into the can, electrical connection between contact tabs and soldering or screw terminals and riveting of the can for a tight seal.

7. Post-forming („Burn-in“) to heal the cut edges of the foil. Main reasons for the post-forming are unformed and cut edges of the anode foil, cracks in the oxide layer that appear during winding, and (to a lesser extent) damages at the joints of the connecting tabs.

8. 100% in-line control of the vital electrical parameters (capacitance, dissipation factor, and leakage current.

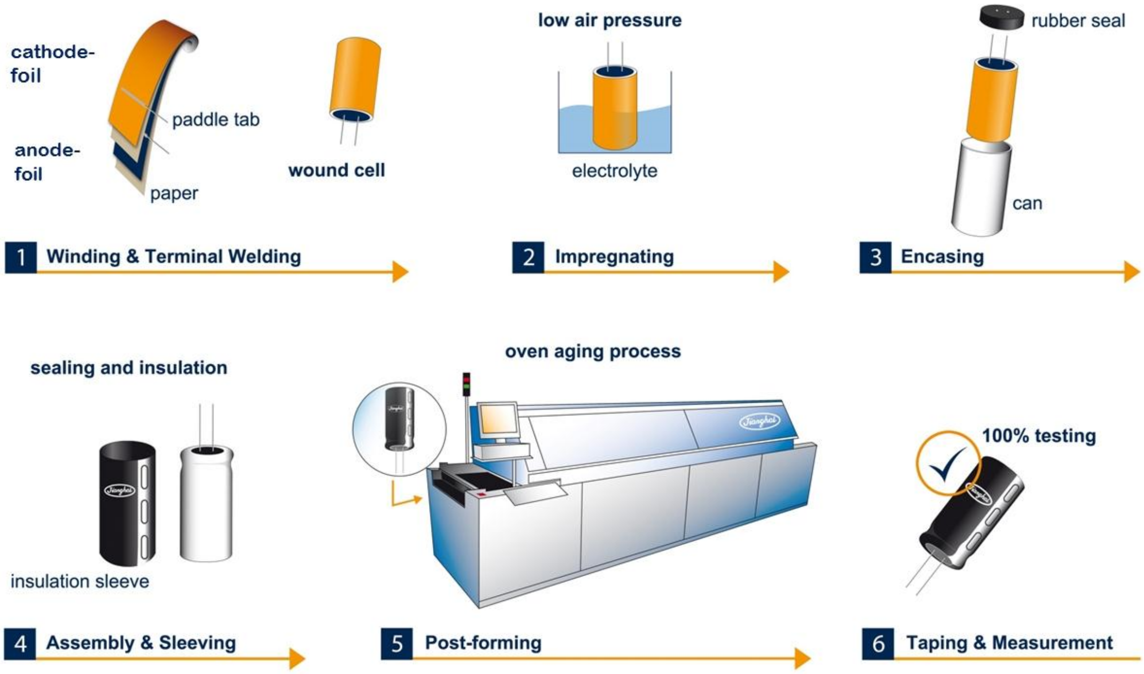

Fig. 3: Process steps from the pre-material to the capacitor

In particular, process steps 2 and 7 have great influence on the reliability of e-caps under operation. Jianghai pursues the target of maintaining a sufficiently high distance of the forming voltage from the rated voltage and a reasonable dwell-time during post-forming to ensure high reliability. As the forming voltage is commonly not indicated in the datasheets, the final user of the components has a hard time to use this parameter as a performance indicator. By asking the e-cap supplier and by comparing the leakage current ratings, the end user may draw his conclusions with respect to the design philosophy of the e-cap manufacturer. In times of rising material and energy prices, even some well-known manufacturers resort to lowering the forming voltages of running series. From a quality perspective, Jianghai considers these “cost-optimization measures” being not acceptable.

Definitions of voltage proof

Even a single occurrence of a voltage out of the permissible range (green and yellow-colored areas in Fig. 4) can already lead to permanent damage of the electrolytic capacitor. For safe and reliable operation of electrolytic capacitors, the following definitions are therefore of central importance.

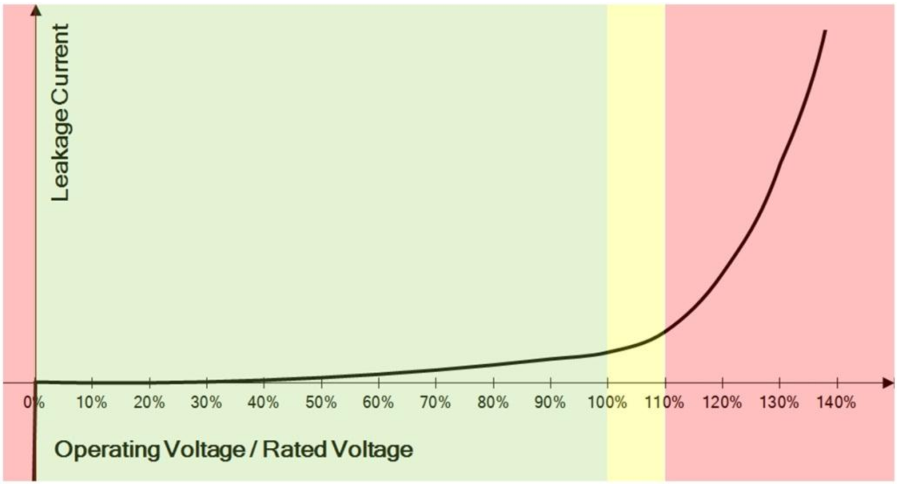

Fig. 4: Typical course of the leakage current vs. operating voltage for a high-voltage capacitor

Reverse voltage (IEC 60384-4, 4.15)

Aluminum electrolytic capacitors as polarized components must always be connected with correct polarity. Applying reverse voltage would mean that the thin (air-) oxide layer on the cathode would take over the task of the dielectric film. Since this oxide layer is very thin, it typically has only a "dielectric strength" of 0.7 ~ 3 volts. Exceeding this voltage triggers an electrochemical reaction that grows the oxide layer on the cathode foil, which is associated with the formation of hydrogen gas and heat. A reverse voltage may (depending on the voltage and power supply) lead to the destruction of the component due to overheating, overpressure and dielectric breakdowns. Therefore, Jianghai does not allow any operation of capacitors under reverse voltage conditions (red area on the left in Fig. 4).

Rated Voltage (IEC 60384-4, 2.2.3 ~ 2.2.5)

The rated voltage is printed on the capacitor and specified in the datasheet. It represents the maximum value in the entire temperature range of the electrolytic capacitor. The continuously applied operating voltage on the capacitor (including any superimposed alternating voltage) shall not exceed the value of the rated voltage. The peak value of superimposed ac and dc voltages must always be located in the green area of Figure 4, while the maximum permissible ripple current must not be exceeded.

Surge Voltage (IEC 60384-4, 4.14)

The surge voltage indicates the maximum voltage value that may be applied during the life at a frequency of 1000 cycles (each with a dwell time of 30 seconds and a pause of 5 minutes and 30 seconds) without causing any visible damage to the capacitor or a capacitance change of more than 15%. For capacitors suited for elevated requirements (the normal case in professional industrial applications), a maximum of five tests per hour at upper category temperature is conducted. For capacitors with a rated voltage of up to 315 volts, a surge voltage of 1.15 times the rated voltage applies, and for capacitors with a rated voltage exceeding 315 volts, a surge voltage of 1.10 times the rated voltage applies (yellow area in Figure 4). Jianghai safeguards the surge voltage strength by carefully reforming at a sufficiently high post-forming voltage. If smaller surge voltages are shown in the data sheets, this may be an indication for a cost-optimized manufacturing process (shorter times and / or lower post-forming voltages in the oven)

Impaired surge voltage performance may also be the result of inadequate pore structures, which were initially furnished with a high dielectric strength (and thus hard to distinguish from components of higher quality while being new), but over the life these capacitors exhibit a larger drift in the parameters and therefore tend to be more susceptible to damage by surge voltage. Even if these components can be exposed to very high allowable current profiles, any unexpected voltage surge may cause a sudden capacitor failure.

Transient Voltage (IEC 60384-4, 4.22)

Transient voltages range above the specified operating voltage range given in the data sheet (red area on the right in Figure 4). Nevertheless, electrolytic capacitors can in principle withstand very high, short-term, transient voltages, if the energy content is low. Voltages beyond the surge voltage lead to high leakage currents and a voltage limit similar to a zener diode [3]. When the electric field strength is too high for the electrolyte, it can directly cause a short circuit. But even if the electrolyte withstands the applied voltage, electrochemical processes lead to a further formation of oxide on the surface of the anode foil, accompanied by heat and hydrogen gas formation, and after a certain time, the safety vent will be engaged.

If in an application transients are expected, Jianghai has the technical possibilities for the optimization of anode foil, electrolyte, and paper in order to provide a specific solution within the physical limits. Since almost all of the materials and process steps have an effect on the stability of the component and its dielectric strength, there are complex interactions of all parameters involved in the design of the components. Jianghai offers its customers a close collaboration to develop optimal solutions for engineering and procurement.

Summary

By their individual voltage proof, aluminum electrolytic capacitors influence the reliability of the electronic devices they are mounted in. A thorough knowledge of some of the key parameters of these components is necessary to ensure the reliable design of electronic devices.

The definitions of voltage proof and the most important influence factors on voltage proof are explained. As a practical tool, a qualitative graph of permissible and forbidden voltage ranges hints helps as a guideline to the successful application of electrolytic capacitors.

The applicability of the general guidelines depends on the specific product type and the particular application. Consultations with the supplier are essential to get guidance throughout the design project and to confirm any estimates.

References

[1] Albertsen, A., Lebe lang und in Frieden! Hilfsmittel für eine praxisnahe Elko-Lebensdauerabschätzung, Elektronik Components 2009, 22-28 (2009)

[2] Albertsen, A., Auf eine sichere Bank setzen – Zuverlässigkeit von Elektrolytkondensatoren, Elektronik Components 2010, 14-17 (2010)

[3] Imam, A.M., Condition Monitoring of Electrolytic Capacitors for Power Electronics Applications, Dissertation, Georgia Institute of Technology (2007)

[4] Venet, P., A. Lahyani, G. Grellet, A. Ah-Jaco, Influence of aging on electrolytic capacitors function in static converters: Fault prediction method, Eur. Phys. J. AP 5, 71-83 (1999)

Company Profile

Jianghai Europe Electronic Components 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 1958 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 radial, snap-in and screw terminal electrolytic capacitors.

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Author

Dr. Arne Albertsen studied physics with a focus on applied physics at Kiel University. Following diploma (1992) and doctoral thesis (1994), both on stochastic time series analysis from a biophysical membrane transport system, he pursued an industrial career in plant construction of specialized waste water treatment and renewable energy generation technologies. In 2001, he started to work with leading manufacturers of electronic components like BCcomponents, Vishay, and KOA. He worked in managing positions in design-in, sales, and marketing for passive and active discrete components until he joined Jianghai Europe Electronic Components in November 2008. In his current position as manager sales and marketing, Dr. Albertsen is responsible for the support of European OEM accounts and distributors.

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