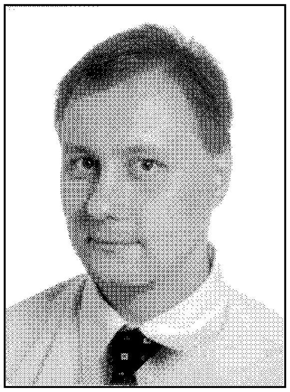
HIGH VOLTAGE ALUMINUM ELECTROLYTIC CAPACITORS: WHERE IS THE LIMIT?



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Abstract

The most basic feature of a capacitor which defines the reliability of the component is the voltage capability. However, the voltage capability of the same component can vary significantly depending on the duration of the different voltage bias levels occurring in a real application. Cost issues often dictate that safety margins be minimized, yet the reliability of the design must be maintained. The present paper attempts to give insight into the behavior of aluminum electrolytic capacitors operated "on the edge" by applying various bias levels near and over the rated voltage. In addition, experiments and test methods which Evox Rifa use in capacitor development to simulate different voltage conditions occurring in real power electronics applications are described.

Introduction

Large, can-type aluminum electrolytic capacitors are widely used as bus capacitors in variable speed drives, UPS systems and inverters, where reliability of the systems is of the utmost importance. For this reason special attention is paid to the reliability of the electrolytic capacitors in order to secure a long life-time in a given application. One of the most critical application parameters of an aluminum electrolytic capacitor is its voltage capability, typically expressed in terms like rated or working voltage, surge voltage, transient voltage, etc. Exceeding the voltage capability (even for a few milliseconds) can result in the immediate failure of the component, or its performance can be deteriorated over the longer term.

The problem for design engineers is that it is often impossible to determine the exact maximum voltage which will never be exceeded in the application, especially when considering short duration transients. The question is further complicated when using capacitor banks where the voltage on an individual capacitor is influenced by the capacitance of other capacitors, which can vary from component to component and can also change over time.

The usual solution for the problem is to require a safety margin between the voltage capability of the component and the expected maximum bias in the application. However, cost optimization requirements tend to drive design engineers to reduce the safety margin as much as possible. In order to do that successfully without undue risk the engineer must know both the characteristics of the application and the actual voltage capability (steady state, surge and transient) of the capacitor being used.

In order to assist design engineers in choosing the optimum electrolytic capacitor, Evox Rifa has studied and characterized the performance of its components in detail. The objective of the present paper is to give insight into the behavior of aluminum electrolytic capacitors operated “on the edge” by applying various bias levels near and over the “rated voltage.” In addition the paper also deals with the experiments and test methods Evox Rifa adopted to probe the voltage capabilities of high voltage electrolytic capacitors in different conditions.

Construction of an Aluminum Electrolytic Capacitor

A wet aluminum electrolytic capacitor is generally comprised of a cylindrical winding of aluminum foils separated by papers impregnated with a liquid electrolyte based on various organic solvents (Figure 1). The anode and cathode foils are made of aluminum which is etched in order to increase the active surface. The anode foil is usually electrochemically oxidized (formed) to 30-40% higher voltage above the rated voltage of the capacitor, producing a thin layer of aluminum oxide film (dielectric). On the contrary the cathode foil is oxidized only up to a few volts regardless of the rated voltage. The anode and the cathode foils are contacted by aluminum tabs which are extended from the winding and are attached to the aluminum terminals. Tab foils are not etched but they also feature an oxide film made by electrochemical oxidization. Terminals are molded into the plastic cover. The wet winding is tightly sealed into an aluminum can. There is a small hole in the cover which is plugged by a rubber safety vent.

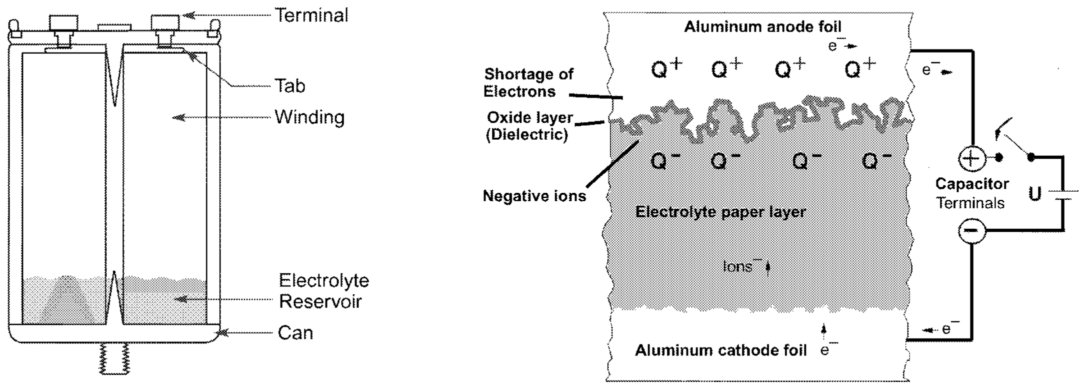

Figure 1. Construction of a typical screw terminal capacitor made by Evox Rifa.

Reversed Voltage

Aluminum electrolytic capacitors are usually manufactured with fixed polarity and may not normally be reversed. Reversing polarity would mean that the dielectric would be the oxide film on the cathode foil instead of that on the anode foil. Since the oxide film on the cathode foil is much thinner it is able to function as a dielectric only up to a few volts (1-3V) in reversed mode. Larger reversed voltages would start an electrochemical reaction of oxidizing the cathode foil. Such a reaction would mean that:

- All available current in the circuit would be concentrated there. (Figure 2.)
- Depending on the available current enormous heat could be produced within a short time.
- Hydrogen gas is developed on the original anode foil.

Depending on the current and the time lapse of the reversed polarity situation, the safety vent may break or in very serious cases the enormous heat may generate fire. However a reversed polarity of 1-3V is in accordance with the oxide film thickness on the cathode foil. Thus it does not usually cause any problems. The right side of Figure 2 shows that the reverse current flow does not increase substantially until the reverse voltage is made greater than about 3 volts.

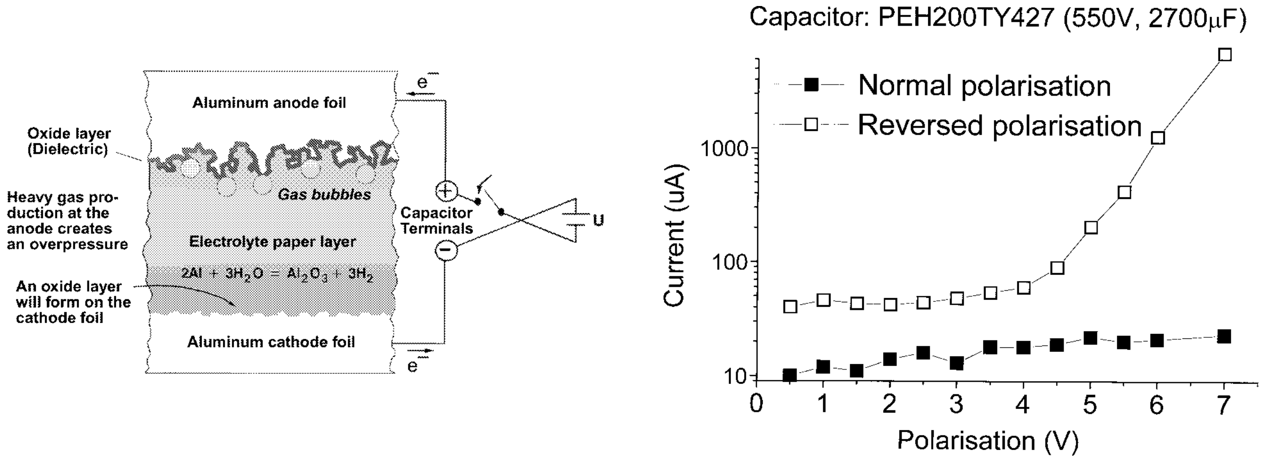

Figure 2. Reversed voltage operation.

Over-Voltage I: Constant Over-Voltage

By increasing the polarization bias on the capacitor the inner parts are exposed to increasing field strength. If the field strength is sufficient, charge transfer could happen through the dielectric. These isolated discharges can grow like an avalanche causing partial discharge, known as sparking because of its audible character. If these partial discharges – at the voltage level of the application – are too frequent, or their magnitude is sufficiently large, they can lead to a total dielectric breakdown and a catastrophic failure of the component. The term "catastrophic failure" refers to the state when physical evidence of damage can be seen on the inside parts.

Definition of the test procedure

Due to the delicate nature of the early discharges, a unique detector was constructed to capture and study the phenomenon. It captured tiny voltage drops on the microvolt level (sparks below the audible limit) with a time resolution corresponding to isolated or minor partial discharges. It also captured the disturbances with a time resolution of nanoseconds which were related to avalanche characteristics. See Figure 3.

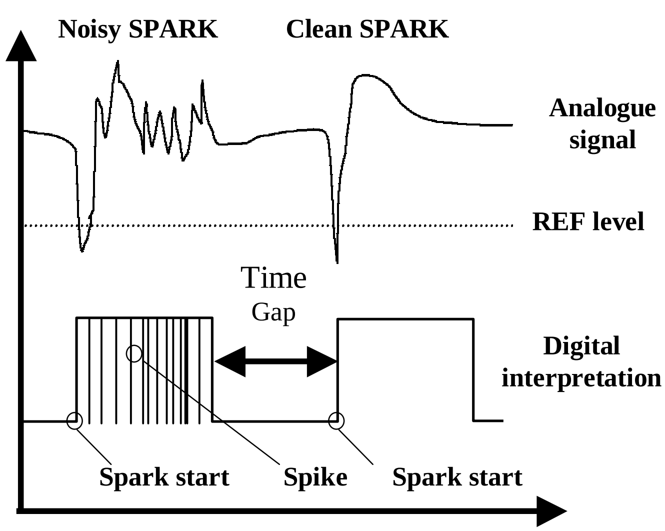

Figure 3. Schematic function of the sparking detector.

Discharges can involve terminals, tabs, anodic foils on the positive side and terminals, tabs, cathode foil or the aluminum can from the negative side with the assumption that they are all wet by the electrolyte. Because of several theoretical and practical reasons tabs were selected as the test objects for the partial discharge studies. They were placed into a thermostated beaker of electrolyte and then were polarized with a constant current power source of 333uA/cm^2.

Results of the test

A typical discharge vs. voltage behavior for a given construction of an Evox Rifa capacitor is shown in Figure 4. The parallel measurements were very reproducible and the number of discharges or "sparks" always increased exponentially above a threshold value.

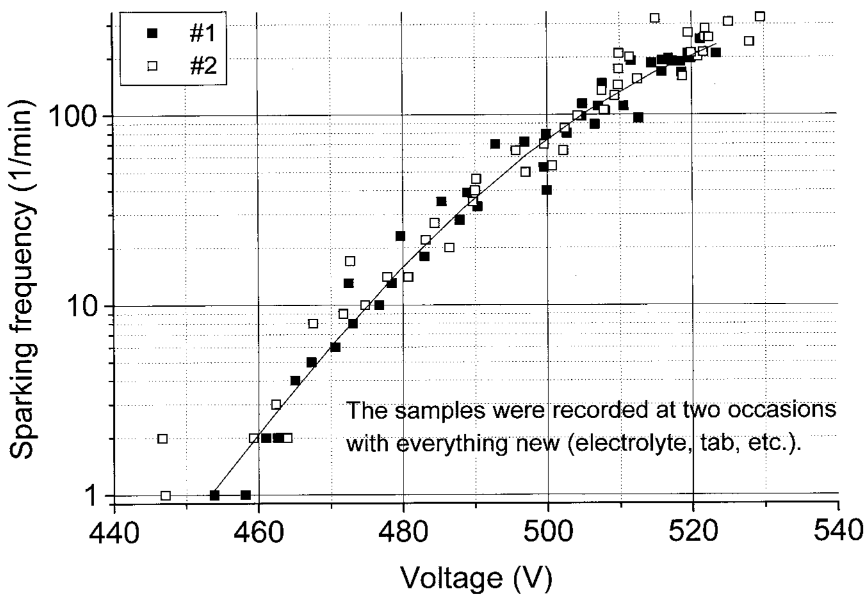

Figure 4. Typical discharge characteristics at voltages near to and over the rated voltage for a new electrolyte formulation designed for 450V capacitors.

The upper voltage limit of the safe operating area (or the so-called sparking voltage) was set to a sparking frequency of 10. This definition would still result in somewhat lower values than the widely accepted and used audible signal, which was first observed when the sparking frequency was about 20-30.

The above measurements were extended into further studies:

- What construction/application parameters affect the safe operating area positively and negatively.
- How other capacitor manufacturers deal with the phenomenon (Table 1).

Table 1. Comparative sparking voltage measurements on products from various capacitor manufacturers at room temperature. (Please note that sparking voltage values specified here are usually 10-20V lower than those measured with the traditional way.)

Origin	Europe	Asia	Evox Rifa	Europe #1	Europe #2	Evox Rifa
Rated voltage (V)	450	450	450	500	500	500
Sparking voltage (V)	447	440	460	533	535	545

We observed e.g. that higher temperatures had a considerable negative impact on the limiting voltage of the safe operating area as Figure 5 demonstrates for two different types of tabs.

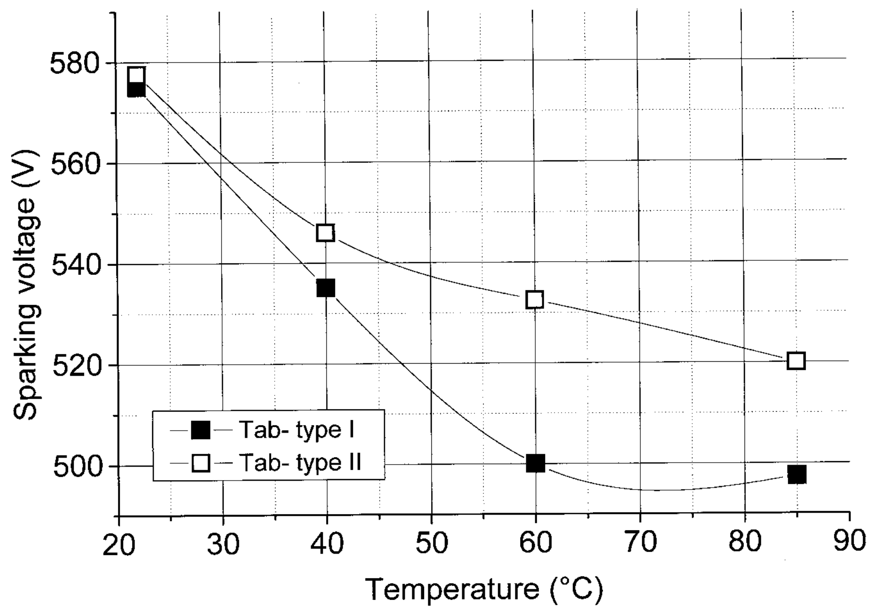

Figure 5. Effect of temperature on the behavior of different types of tabs. Type II could be used for 500V capacitors with the given electrolyte, while type I is limited to 450V construction with the same electrolyte.

From the above experiments important conclusions can be drawn for design engineers of power electronic systems:

- There is a very sharp voltage limit for a reliable continuous operation of wet aluminum electrolytic capacitors. Consequently, a few volts safety margin could mean orders of magnitude in reliability. Or vice versa…
- Over-voltage specifications like surge voltage, transient voltage, etc. should be looked on as sources of high risk, where stability is on the brink. Therefore accurate knowledge of the parameters are required both from circuit designers and capacitor producers in order to find the suitable component.

Over-Voltage II: Pulses With Various Types

Though capacitors are designed to be operated with highest reliability up to the rated voltage, over-voltage pulses of various types can hardly be excluded in a real application. These pulses – as concluded before – are sources of risk; however they do not necessarily permanently deteriorate the performance of the component. In an advanced capacitor construction over-voltage pulses are already considered in the design phase of the capacitor. Later on it is tested and specified.

On the other hand, over-voltage pulses can be of as many different types as there are applications and thus it is difficult to trim every single capacitor design to the specific needs. Instead, capacitor manufacturers tend to use standard test methods with various pulses to describe the over-voltage capabilities of their capacitors. An advantage of the standard methods is that one may readily compare between products of different manufacturers. Evox Rifa uses three classes of over-voltage pulse tests in order to characterize its high voltage products. In the following paragraphs these methods will be discussed with the focus on what they really tell a circuit designer.

Surge Pulses – Surge Voltage

Definition of the test procedure for high voltage capacitors

110% of rated voltage is applied as a 30 seconds long pulse, followed by a 330 second no-load period at the upper category temperature. The pulse is repeated 1,000 times consecutively. Charging is done with a high enough current to obtain a charge time of 0.1 sec.

Criteria after test

No visible damage should be observed, including electrolyte leakage. Capacitance change should be less than 10%; leakage current and tangent of the loss angle at 100 Hz should not exceed the maximum specified in the base specification.

Approaching the situation from the construction side it could be said that the oxide layers of the anode foil and the anode tab foil should be thick enough on most areas to cope with the pulses. However, oxide films on the edges are not thick enough since they were newly built up during the burn-in process, which usually goes up only to the rated voltage or a little above. It means that the current will be concentrated along the edges of the anode foil and the anode tab. In addition, the increasing bias will enter the region where discharges for sure will occur.

The question is whether the magnitude and/or the duration of the pulse is enough to start extended avalanching discharge, or will the component stabilize within a pulse or two. Figure 6 shows a typical Evox Rifa capacitor with a rated voltage of 550V. It can be seen that the leakage current starts with high values, after which the capacitor stabilizes and the leakage current decreases. Though there is no direct coupling between the leakage current and partial discharges in a sense that below a certain leakage current there are no discharges, it is assumed that lower leakage current indicates reduced risk for partial discharges. It can also be noticed that further stabilization occurs as the number of cycles increase, which is manifested in lower current values and less variation.

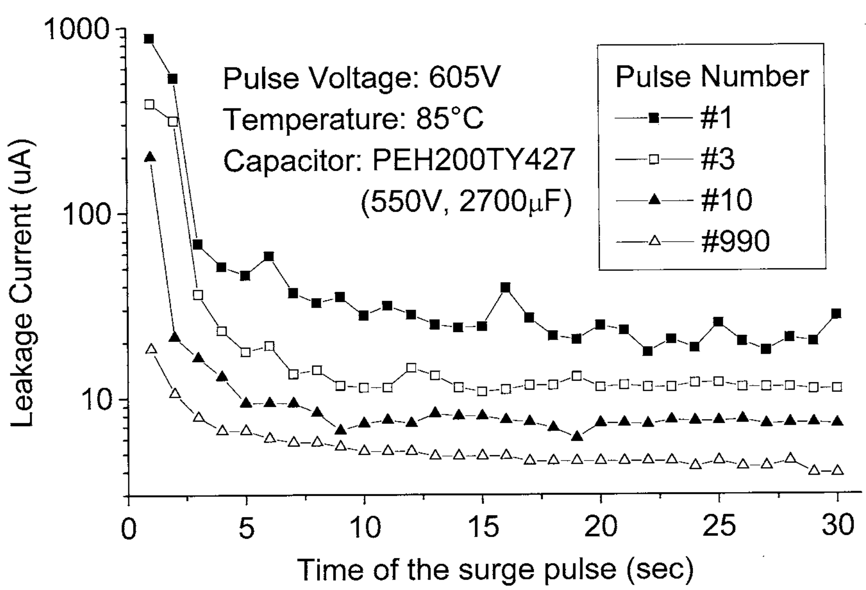

Figure 6. Leakage current behavior during surge pulses.

Transient Pulses – Transient Voltage

The transient voltage test is designed to simulate pulses on the network which are generated when electrical systems are being switched on or off. The aim of this test is to determine the maximum voltage of the transient pulse which the capacitor can stand without failure.

Definition of the test procedure

A capacitor bank loaded to a given charge is discharged onto the tested capacitor. The effect will be a powerful but short pulse on the test object at room temperature. If the capacitor is capable of absorbing the pulse without failure, a new pulse is given with 50V higher bank voltage within 30 seconds. The capacitor is discharged between the pulses, about 15 milliseconds after each pulse. The pulses are continued as long as the capacitor is functioning.

Result of the test

The primary result is the highest measured voltage level on the capacitor before failure, defined as the transient voltage. Secondary results are the largest inrush current and the ratio between the maximum absorbed charge (without failure) and the nominal charge. Figure 7 shows an example where the capacitor was able to absorb the pulse without failure, and when the capacitor failed to absorb the pulse. The latter shows that the voltage, instead of remaining at a high level, dropped sharply after the beginning of the pulse.

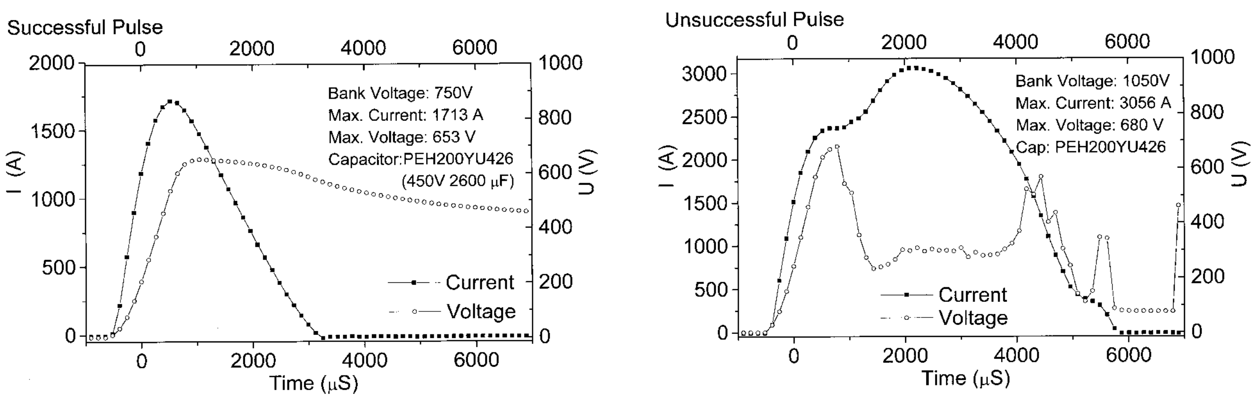

Figure 7. Successful and unsuccessful transient pulses on the same capacitor.

Transient pulses are significantly different from surge pulses because they are much shorter in time (on the level of milliseconds). This causes a very special environment inside the capacitor:

- Enormous current can flow for a short time.
- Temporarily, voltage levels in the test capacitors can exceed the capability of the oxide film on the anode foil or tab.
- Virtual capacitance shortly after the pulse can exceed the nominal capacitance.
- Consequently, the capacitor can temporarily store several times higher energy than in continuous operation.

Experimental data indicates that failures of capacitors could be linked to the high inrush current rather than to the electric field strength. We suspect that this has to do with the spatial distribution of the current.

If the total current is high enough and the electrolyte system permits the generation of avalanches of discharges, then the majority of the total current could be concentrated on discrete "weak points." The thermal and electric effect of the locally concentrated current can make that capacitor fail.

If the electrolyte is unable to develop heavy discharge avalanches, the inrush current is dissipated over a larger area and the capacitor can safely adsorb the pulse. Modification of the electrolytes and other construction parameters can positively influence the current threshold where critical avalanches occur. Thus the transient capability of the component can be improved to some extent.

However, it is generally understood that these pulses may deteriorate the quality of the oxide film since even minor discharges can create physical damage (Figure 8). Once discharges occur the originally fairly flat surface of the tab foil will feature large numbers of protrusions whose geometry will attract newer discharges. Generating more and more weak points by such pulses, the risk of fatal discharge avalanche at the next pulse will be larger.

On the other hand the reliability of continuous operation of the capacitor up to rated voltage and temperature appears not to be affected significantly by the number of pulses. This can be due to the fact that the pulse-pricked oxide layer can easily be repaired by the electrolyte system's self-healing process up to the rated voltage. However with transient pulses of higher voltage levels this would not be possible.

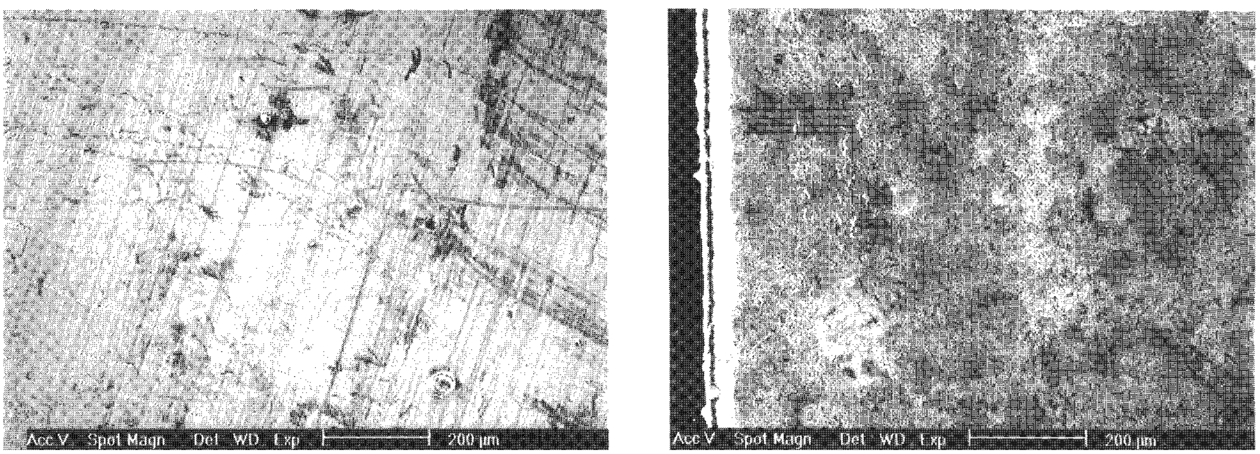

Figure 8. Oxide film exposed to high number of partial discharges. Scanning Electro-micrograph (SEM) of a tab foil area where it ***was*** *and* ***wasn't*** *exposed to frequent partial discharges. The large number of protrusions on the right picture is believed to be the result of discharges.*

Double-Load Pulsing

Capacitors in real applications are usually exposed to minor, but large numbers of transient pulses during their operating time. Therefore the voltage of the highest possible transient pulse (transient voltage) might not give the information a design engineer wants to know most when it comes to over-voltage. In that case the double-load pulsing test can be of great value to the designer. Double-load pulsing exerts less stress on the capacitor than the transient voltage pulsing, but it is testing the endurance of the capacitor more thoroughly by its repetition.

Definition of the test procedure

A capacitor bank, loaded to twice the charge of the test capacitor, is discharged onto the test capacitor at room temperature. 15 milliseconds after each pulse the capacitors are discharged. The pulse will be repeated at 90 seconds intervals until the capacitor fails.

Results of the test

The primary result is the number of pulses a given capacitor construction can stand without failure. Though the inrush current characteristics are always the same, consecutive pulses are not causing an identical effect on the capacitor. Due to the short interval between the pulses, capacitors can "remember" the previous pulses. This phenomenon can be observed in Figure 9 which shows that the charge is somewhat cumulating after each pulse. As a result, after a given number of pulses the capacitor will fail.

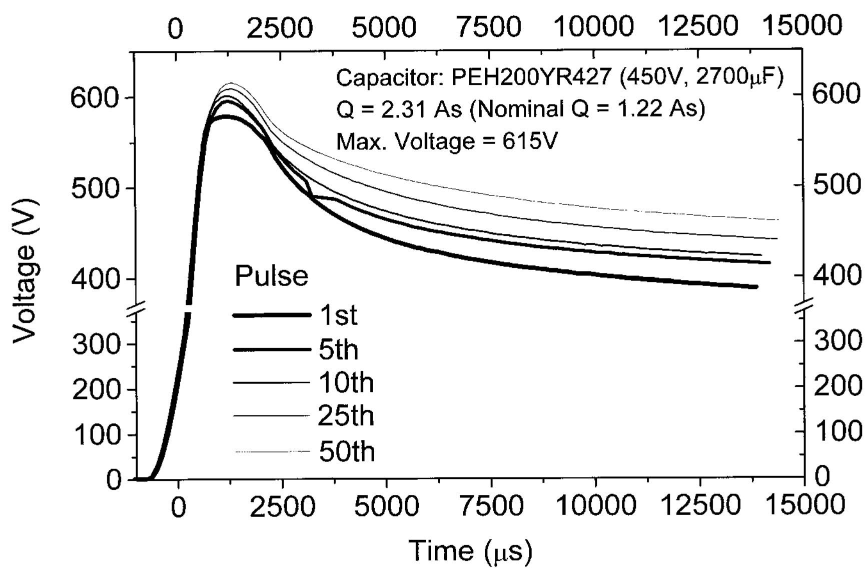

Figure 9. Cumulating charge in a double-load pulsing test.

Conclusion

Power electronic circuits are often experiencing over-voltage pulses from the network. Components of such circuits must be designed by accounting for this phenomenon.

Aluminum electrolytic capacitors are especially sensitive components with respect to voltages beyond the rated limits. Therefore they should be selected with special attention to their over-voltage capabilities. Voltages beyond rated voltage can cause immediate failures or deteriorate performance in the long term, depending on the nature of the events. A few volts of intelligently chosen safety margin – in both rated voltage and over-voltage – can mean orders of magnitude in reliability without prohibitive expense.

Capacitor manufacturers can provide four tests and parameters describing voltage characteristics beyond the rated values: Reversed Voltage, Surge Voltage, Transient Voltage and Double-Load Pulsing. Each test tries to simulate the behavior of the capacitors in different type of voltage conditions which may occur in real applications. With the help of these test results circuit designers can better select aluminum electrolytic capacitors to fit their applications, which would function with higher reliability in spite of being operated "on the edge."