SOLID POLYMER ALUMINUM CAPACITOR CHIPS IN DC-DC CONVERTER MODULES REDUCE COST AND SIZE AND IMPROVE HIGH-FREQUENCY PERFORMANCE

By
Laird L. Macomber, Cornell Dubilier, Liberty, South Carolina 29657 and Joseph G. Rapoza
Cornell Dubilier Electronics, New Bedford, Massachusetts 02744

ABSTRACT

The new, 125 °C, solid polymer aluminum (SPA) capacitors have performance advantages over other types of low ESR capacitors when used as output filters in DC-DC modules. The principal advantage of an SPA capacitor is that its ultra low ESR permits filtering in a DC-DC converter with fewer capacitors. This reduces the cost and size of the converter. Other advantages are ignition free, open circuit failure mode, better filtering from lower ESR, higher peak current capability and more rapid energy transfer. The new type is available as Cornell Dubilier Type ESRH.

While SPA capacitors are inherently reliable, they do have a wear out mechanism. Entrapped moisture causes a steady increase in ESR. However, the new 125 °C version has eliminated most of the moisture entrapped during manufacturing and can provide an expected life of more than 10 years in typical, hot running, DC-DC modules.

1. INTRODUCTION

While solid polymer aluminum (SPA) electrolytic SMT capacitors have been available for several years, and have demonstrated sufficiently low high-frequency ESR as to out perform solid tantalum capacitors in output filters in DC-DC converters. The new Type ESRH SPA device rated for 125 °C operation is a breakthrough for hot running DC-DC modules. A modern DC-DC converter module routinely incorporates an integrated metal substrate (IMS) to handle higher currents, reduce the thermal resistance and lower the operating temperature of magnetic components and switching devices. However, the IMS is usually permitted to operate up to 125 °C and this requires the output capacitors to be capable of 125 °C operation too.

This paper shows the performance advantages of the new Type ESRH, 125 °C, SPA capacitor in DC-DC modules. Low ESR solid tantalum chip capacitors, low ESR SMT aluminum capacitors and SPA chip capacitors are compared in popular DC-DC module capacitor ratings. Comparisons are for capacitance of more than 20 µF and rated voltage of 10 V or less. Comparison to ceramic capacitors is not included because the Class 3 ceramic dielectrics required for MLCC capacitance values in the 10s and 100s of microfarads lose more than half their capacitance when operated at 85 °C or hotter.

Then this paper proceeds to explain the product changes that have permitted SPA capacitors to increase maximum operating temperature from 105 °C to 125 °C. It discusses life and reliability models that demonstrate expected life of more than 10 years in most applications.

The ESR of the output capacitors in a DC-DC module sets the level of unwanted output ripple voltage because at the 200 to 900 kHz switching frequencies of modern DC-DC modules the capacitive reactance is negligible compared to the ESR. For comparable CV values a SPA capacitor has an ESR at 100 kHz, typically one seventh to one tenth of low ESR tantalum chips, and one third of tantalum polymer types. This ultra low ESR accomplishes filtering in a DC-DC converter with fewer capacitors. Fewer capacitors are plenty enough because of the combined effect of the SPA's high ripple current handling capability of

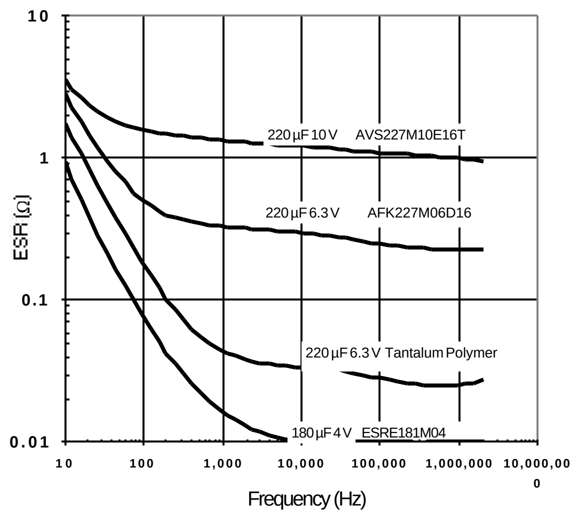
2 or 3 amps, peak current capability greater than 60 amps at 1 kHz, and the ability to deliver more energy in less time.

While solid tantalum capacitors are modeled as having no wear out mechanism and thus have a failure rate that decreases with time, SPA capacitors do have a wear out mechanism, and the ESR gradually increases. The rate of ESR increase is determined largely by entrapped moisture. This paper explores and models the rate of ESR increase as a function of ambient humidity.

Expected life is defined as the time until the 400 kHz impedance has reached two times its initial value. Expected life increases with reduction of applied voltage, ambient temperature and relative humidity. Relative humidity has the most effect. This paper models expected life as a function of these three environmental variables and demonstrates more than 10 years life for all but the most extreme applications.

2. ADVANTAGE: LOWER ESR

As said, the big advantage of SPA capacitors is their low ESR at high frequency. Compared to solid



tantalum and other SMT aluminum capacitors capable of the capacitance values needed for DC-DC converter output filters the SPA has much lower ESR.

Fig. 1 ESR vs. Frequency for SMT Output Filter capacitors

Referring to Fig. 1, ESR descends more than two decades as you move from standard SMT aluminum Type AVS, to low ESR SMT aluminum Type AFK, to low ESR tantalum polymer type and finally to the SPA Type ESRE. In the frequency range from 1000 Hz to 100,000 Hz the ESR of the SPA chip is one third or less than the ESR of the tantalum chip. This demonstrates that one SPA chip can provide the same filtering and the same output ripple voltage for a DC-DC converter as could three tantalum chips.

In this case, the SPA capacitor has an ESR one third of the ESR of the new tantalum polymer chip. That’s the lowest ESR tantalum available.

3.) ADVANTAGE: FASTER DYNAMIC TRANSIENT RESPONSE

The slow transient response of power supplies embedded in equipment can cause CPUs to malfunction because the supply current ramps up too slowly. This is shown in Fig. 2. An appropriate capacitor across the interface between the supply and the CPU can function as a buffer and provide drive current until the supply output current has ramped up, but, not just any capacitor will do.

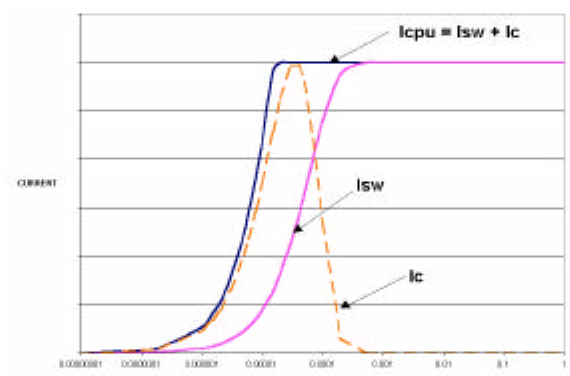


Fig. 2 Capacitor current buffering CPU

The circuit of Fig. 3 tests capacitor transient response capability. The curves of Fig. 4 show a comparison of the transient response for a 180 µF, 2 V SPA capacitor versus a 220 µF, 4 V polymer tantalum capacitor. Polymer tantalum capacitors perform better on this test than do standard, low ESR tantalum capacitors because they have lower ESR resulting from the use of a solid-polymer impregnation of the sintered-tantalum pellet capacitor. This polymer is similar to the one used in SPA capacitors.

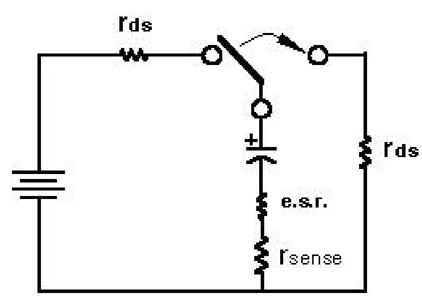


Fig. 3 Capacitor Transient Response Measurement Circuit

Both capacitors were charged to 2 V and discharged into a short-circuit. The curves show that the SPA capacitor delivers a much higher peak discharge current and fully discharges in significantly less time. The peak current for the SPA capacitor is 70 amps and for the tantalum capacitor, 30 amps. The SPA fully discharges in 15 µs, and the tantalum capacitor takes 30 µs. While the two capacitors exhibit the same initial di/dt of 40 A/µs, the SPA delivers half its energy in half the time required for the tantalum capacitor, 12.3 µs versus 24.5 µs.

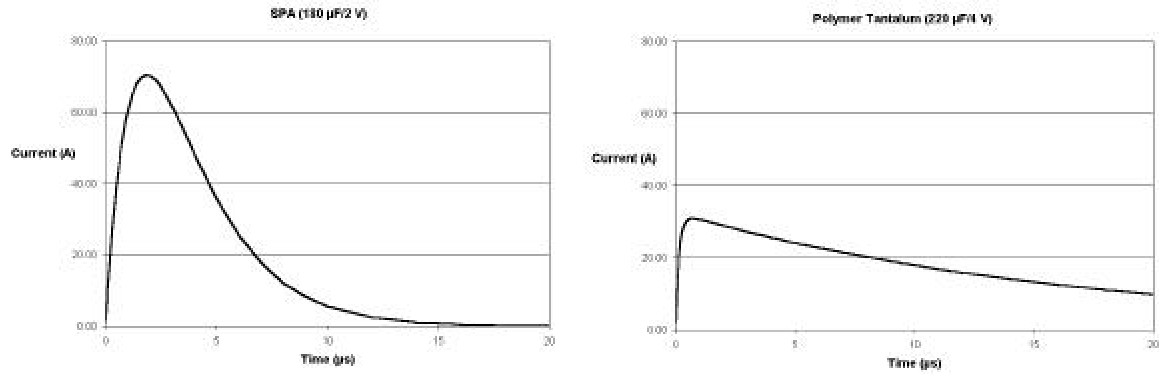


Fig. 4 Transient Response of a SPA Capacitor vs. Tantalum Polymer Capacitor

4. ADVANTAGE: SHORTER TIME CONSTANT

When a capacitor is used as a source stiffening capacitor and is buffering the supply by delivering initial current, a lower RC time constant allows delivering significantly more current. The table below shows a comparison between a 33 µF, 8 V SPA and a 33 µF, 10 V tantalum (T491D336(1)010AS).

Capacitor Type	Capacitance (µF)	ESR @ 400 kHz (W)	Time Constant (µs)	Percentage (%)
Tantalum	35.046	0.21	7.36	100
SPA	37.362	0.0155	0.579	8

The SPA capacitor above, runs 92% lower RC time constant than same rating tantalum chip, with best performance typically at 100 kHz.

5.   ADVANTAGE: HIGHER PEAK CURRENT

With microprocessor speeds exceeding a gigahertz and CPU peak current demands of 80 amps and more, output filter capacitors are being hit hard. The days when you could conservatively hold the source impedance to one ohm per volt to protect the output capacitor are long gone. This recent demand for higher peak currents and at faster repetition rates has moved ahead of the ability of the capacitor industry to respond, and no industry or manufacturer standards exist for specifying peak current capability. However, The transient response test circuit of Fig. 3 is also suitable for use to test a capacitor's peak current capability, and while there are no absolute requirements, it is possible to compare performance of different types of capacitors.

Replacing the mechanical switch shown in Fig. 3 with two PFET switches and appropriate driving circuitry permits varying the repetition rate.   Thus configured, the test circuit revealed orders of magnitude differences in peak current capability between SPA capacitors and low ESR tantalum capacitors. With a 33 µF, 8 V SPA capacitor in the test circuit, the supply voltage was set to 125% of rated voltage, 10 V, and the repetition rate was set to 1 kHz.. The current pulses occurred twice per cycle with a positive pulse when the power source was applied and a negative pulse when the capacitor was shorted to ground. Initially the current peaks were 60 amps as shown in Fig. 5. After 6 ½ hours of continuous operation the peaks were approaching 40 amps. The following day the current peaks were initially 45 amps; so, the drop in current was apparently caused by a permanent change in the capacitor. With a 33 µF, 10 V solid tantalum capacitor in the test set, it was a different story.

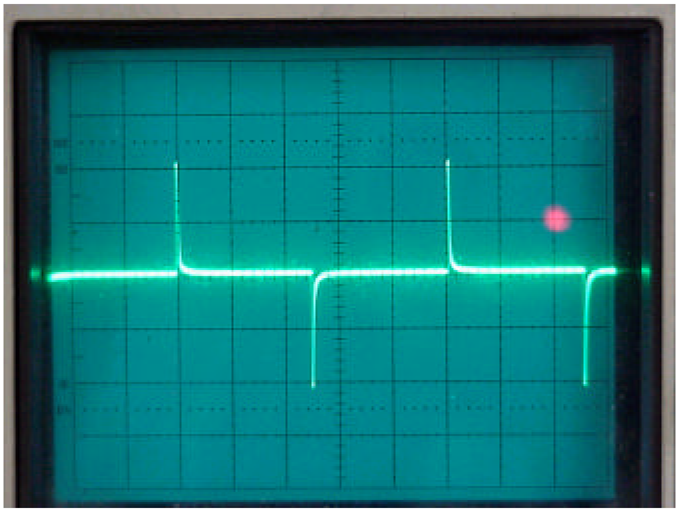


Fig. 5 Output current from 33 µF 8 V SPA capacitor.

The supply voltage was again set to 10 V but in this case 10 V was rated voltage. The repetition rate was again set to 1 kHz. Initially the current peaks were 45 amps; however, in one minute and 55 seconds the capacitor erupted in flames as shown in Fig. 6. A second capacitor lasted 2 minutes and 5 seconds before it too burst into flames.

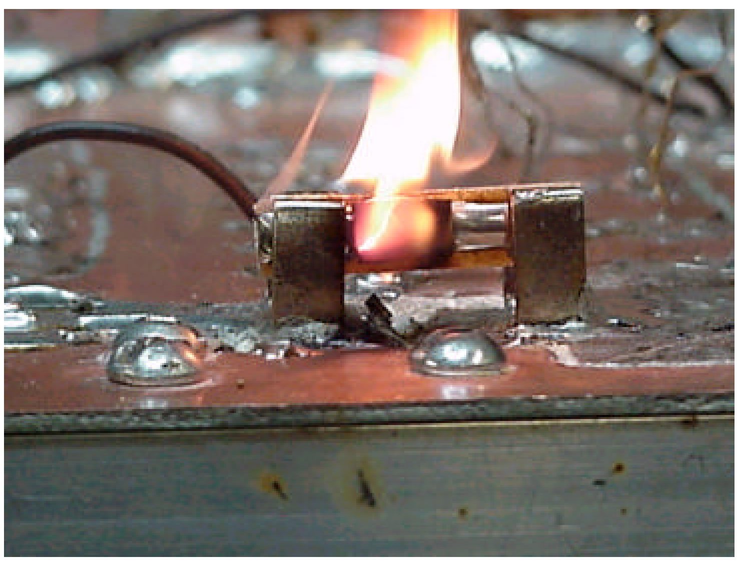


Fig. 6 Two minute Exposure of 33 µF, 10 V Tantalum Capacitor to 10 V, 1 kHz Squarewave

The tantalum capacitor was able to withstand continuous operation at 1 kHz with the supply voltage reduced from 10 to 6.3 V. This is a 60% reduction in power. Note that at 1 kHz and 10 V the SPA capacitor lasted nearly 12,000 times as long as the tantalum capacitor before its performance reduced to the initial performance of the tantalum capacitor.

6. ADVANTAGE: OPEN CIRCUIT, IGNITION-FREE FAILURES

While other capacitor types routinely fail short-circuit when exposed to over voltage or over temperature stress, SPA capacitors are surprisingly free of short-circuit failures. The physical mechanism that prevents short-circuit failures is in the polymer electrolyte. When a short-circuit failure tries to occur, local heating of the polymer converts it to a high resistance, stable compound, and thus effectively self-heals the capacitor. A similar self-healing occurs in solid tantalum capacitors in which the manganese-dioxide (MnO_2) contact electrode is converted to a more resistive manganese pentoxide (MnO_5). However, the conversion of the polymer in SPA capacitors produces better disconnects of damaged material. This is because while MnO_2 must be heated above 600 °C to increase resistivity, the SPA polymer becomes resistive above 300 °C and is open circuit at less than 500 °C.

Demonstrating the reliability, 5080 SPA capacitors tested at 105 °C with rated voltage applied with less than 0.1 Ω source impedance for 20 million units hours exhibited no failures. At 125 °C, 1000 SPA capacitors tested for 3.5 million unit hours also exhibited no failures.

The headline making advantage of SPA capacitors is that they don't support combustion. None of the constituent materials is readily flammable and failures are ignition free. In tantalum capacitors the MnO_2 releases oxygen that supports combustion.

7. DEVELOPMENT OF 125 °C SPA CHIP

The SPA capacitor appears to be an offspring of a delightful marriage between the solid tantalum capacitor with the aluminum electrolytic capacitor. The SPA and its tantalum and aluminum parents create the capacitor's dielectric as an oxide grown on a metal that connects to the positive terminal of the capacitor. However, the SPA's positive side looks like an aluminum electrolytic and its negative side looks like a solid tantalum.

The solid tantalum capacitor starts with an oxidized sintered slug of tantalum powder with a tantalum wire. The tantalum wire connects to the positive terminal of the finished capacitor, and the tantalum oxide connects to the negative terminal through a MnO_2 contact electrode and coatings of carbon and silver paint. The terminals are soldered to the capacitor element and the capacitor element is molded in resin to be the familiar tantalum chip capacitor.

The aluminum electrolytic capacitor starts with an etched and oxidized anode foil, an etched cathode foil and paper separators. Aluminum tabs connect to the foils, the foils and paper wind into a capacitor element, the element is wet with conductive electrolyte and the tabs connect to terminals in the sealed capacitor. The aluminum oxide connects to the negative terminal through the electrolyte and cathode foil.

The SPA capacitor replaces the liquid electrolyte of the aluminum electrolytic capacitor with a solid, highly conductive polymer that becomes solid after it penetrates the pores of the etched aluminum anode foil. Then, like the solid tantalum capacitor, it connects to the negative terminal through coatings of carbon and silver paint.

The high conductance of the solid polymer sets the SPA head and shoulders above its parents. It is 1000 times as conductive as MnO_2 and 10,000 times as conductive as liquid electrolyte.

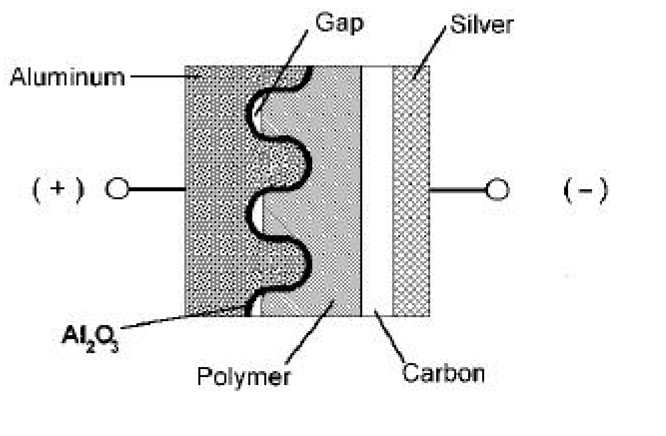


Fig. 6 Construction Diagram for Solid Polymer Aluminum (SPA) Chip Capacitor

The SPA capacitor has been available until now only as a 105 °C rated component. The problem was that if operated continuously at 125 °C the ESR would increase rapidly and would cause the impedance to double in a few hundred hours. The construction diagram of Fig. 6 shows the cause. Moisture trapped during manufacture at the interface between the conductive polymer and the aluminum-oxide dielectric would react at high temperatures and form aluminum hydroxide. The aluminum hydroxide is conductive and appears as a resistive layer in series with the solid polymer. The chemical reaction followed this equation:

$$Al_2O_3 + 3H_2O \rightleftarrows 2Al(OH)_3$$

Introduction of the new Type ESRH capable of continuous operation at 125 °C required changes to the polymer resin and manufacturing environment to avoid entrapping moisture at the polymer aluminum-oxide interface. As shown in Fig. 6 humidity and operating temperature greatly effect expected life.

The expected life equation is

$$L = 1606 \cdot e^{10910\left[\frac{1}{273 + T_a} - \frac{1}{273 + 85}\right]} \cdot e^{550\left[\frac{1}{H_a} - \frac{1}{90}\right]}$$

expressed as a function of ambient temperature Ta in °C and ambient relative humidity Ha in percent.

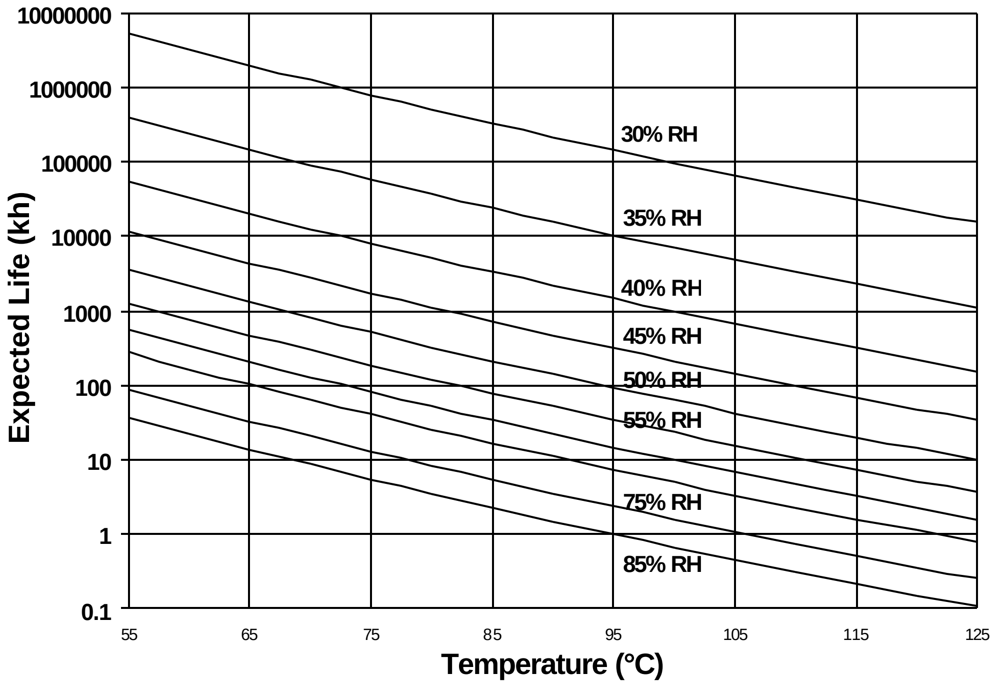


Fig. 7 Expected Life vs. Temperature and Humidity

Conclusion

The new Type ESRH SPA capacitor is suitable for use as an output filter capacitor in the new breed of DC-DC converter modules with IMS backbones. It offers expected lives in excess of 10 years for operating temperatures up to 125 °C at 40% RH and up to 65 °C at 65% RH. It's ultra-low, high frequency ESR permits it to replace three or more solid tantalum capacitors for the same output ripple voltage.

Bibliography

J. Marshall, J. Prymak, E. Reed, "Lowest ESR tantalum chip Capacitor", CARTS '98 Program, The Components Technology Institute, Inc., Huntington Beach, CA March 1998

Ted von Kampen, "Ensure AC Film Capacitor Reliability with Thermal Analysis," PCIM March 2001, pp 56-67.

I. Clelland & R. Price, "Multilayer Polymer (MLP) Capacitors Provide Low ESR and are Stable Over Wide Temperature and Voltage Range," Proceedings of the 8th Annual European Capacitor and Resistor Technology Symposium, October 1994

J Prymak, "Performance Issues for Polymer Cathodes in Aluminum and Tantalum Capacitors," CARTS 2001 Program, The Components Technology Institute, Inc., Huntington Beach, CA, February 2001