Hybrid® Capacitor Applications

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ABSTRACT

Hybrid® capacitors have a lower time constant than other electrochemical capacitors. The behavior of Hybrid® capacitors was evaluated in two applications combining high-rate discharge, limited charging time and current, and high energy density as critical requirements. Capacitance vs. Resistance plots are introduced as an aid to designing capacitors and comparing capacitor performance.

INTRODUCTION

The Evans Hybrid® capacitor combines the best features of both electrochemical and electrolytic capacitors. By using an electrochemical capacitor cathode and an electrolytic capacitor anode, order-of-magnitude increases in volumetric energy density over aluminum electrolytic capacitors have been reached.[1] Employing a dielectric coated anode electrode, the single-cell Hybrid® capacitor is able to withstand high voltages. In contrast to electrochemical capacitors, where cell voltage is limited to the breakdown voltage of the electrolyte, the Hybrid® capacitor cell voltage depends on the breakdown voltage of the anode dielectric. So, cell voltages typical of electrolytic capacitors (up to at least 500 V) can be achieved. Units with cell voltages between 3.5 V and 300 V have been constructed.

A drawing of the internal construction of a Hybrid® capacitor is shown in Figure 1. Figure 2. is a photograph of a one-anode element polypropylene cased tantalum Hybrid® capacitor. The physical dimensions of this unit are 1.40 inch diameter by 0.2 inch high. A partially disassembled unit is shown in the photograph in Figure 3.

A major advantage of the Hybrid® capacitor technology over symmetric electrochemical capacitors is its variable cell voltage. This allows the single-cell Hybrid® capacitor voltage to be

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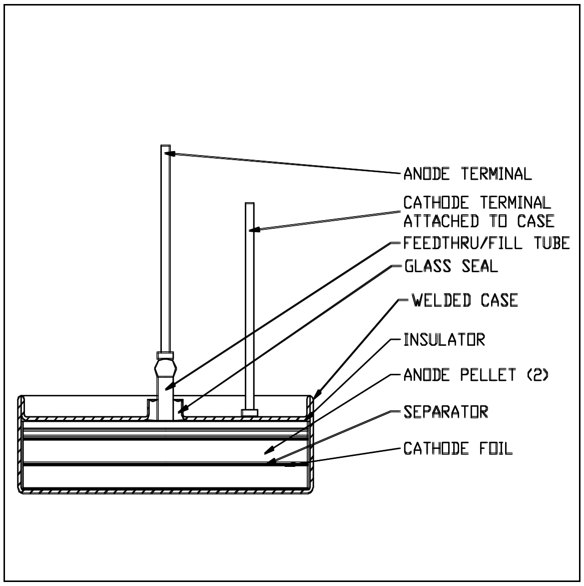


Figure 1. Schematic view showing internal construction of a dual-anode element hermetic tantalum Hybrid capacitor.

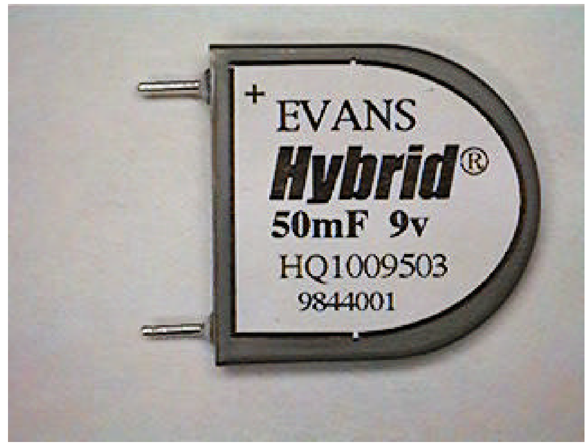


Figure 2. Photograph of the tantalum Hybrid capacitor.

Figure 3. Photograph of a partially dismantled, 3-element polypropylene case tantalum Hybrid capacitor showing stacked arrangement of anode electrodes connected in parallel. The top cathode plate and separator has been removed .

designed for a specific application, eliminating the need for series connection of cells. Because of this, cell voltage balancing ceases to be an issue. Capacitor construction is simplified, enhancing reliability and reducing cost.

In many instances, the RC product or frequency response of a capacitor is more important in an application than its energy or power density. The RC product of tantalum Hybrid® capacitors is on the order of 1 ms. This is comparable to aluminum electrolytic capacitors but one or two orders of magnitude lower than currently available electrochemical capacitors.[1]

Figure 4 is a Bode plot which shows the resistance and reactance (z' and z") as a function of frequency for a tantalum Hybrid® capacitor and an aluminum electrolytic capacitor, both rated at 54 V, 18 mF . The plot indicates that the frequency of self-resonance for the capacitor is about 8 kHz. The RC product for this capacitor is 0.72 ms. Figure 5 is a Nyquist plot of the same data as the previous figure. The Nyquist plot for an ideal capacitor is a straight vertical line, intersecting the X-axis at the ESR value. This shows that the electrical response of a tantalum Hybrid® capacitor is very nearly ideal. Figure 6 plots phase angle vs. frequency for a 54 V, 18 mF tantalum Hybrid® capacitor. An ideal capacitor has a phase angle of -90º.

Another advantage of the Hybrid® capacitor is its relatively low ESR, and its ability to handle very high current levels. These devices are now under evaluation for in use in pulse-discharge power supplies. In one example, an airborne weapon targeting system uses a 54 V, 18 mF tantalum Hybrid® capacitor to provide 200 μs, 150 A discharges (a peak power level of >8 kW) at a repetition rate of 50 Hz. The measured peak power capacity of this capacitor is >20 kW. The calculated Hybrid® capacitor power density, >1 MW/l, is several orders of magnitude greater than the power density of state-of-the-art electrochemical capacitors using carbon electrodes.

DISCUSSION

Method of Comparison

Often, the designer is faced with with a choice among several competing candidate capacitor technologies. In selecting a capacitor for a specific application, performance requirements such as capacitance, working voltage, and ESR must be determined. To decide which is the best alternative, there must be a means of predicting and comparing the performance. We have found a particularly useful and simple graphical method of comparison which we have used in each of the following examples. The general graphical form is shown in Figure 7. The plot shown is drawn for a specific *application* regardless of the *capacitor* under evaluation. The particular model used in this example is that of a simple series R C circuit. The equation for capacitance as a function of resistance is

$$C = It/(\Delta V - IR)$$

where C is capacitance in farads, t is time in

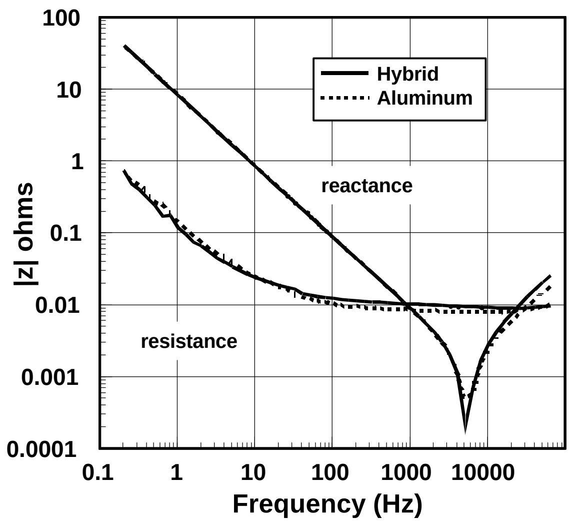


Figure 4. Bode plots for a polypropylene case tantalum Hybrid capacitor and an aluminum electrolytic capacitor, both rated at 54 V, 18 mF.

Figure 5. Nyquist plot for a 54 V, 18 mF polypropylene case tantalum Hybrid capacitor.

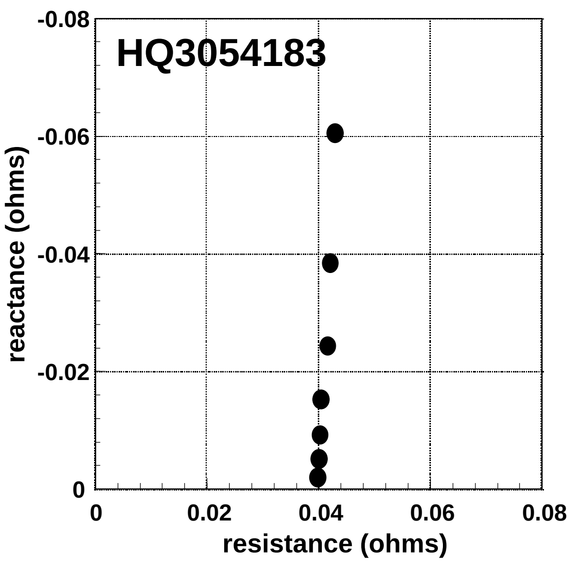
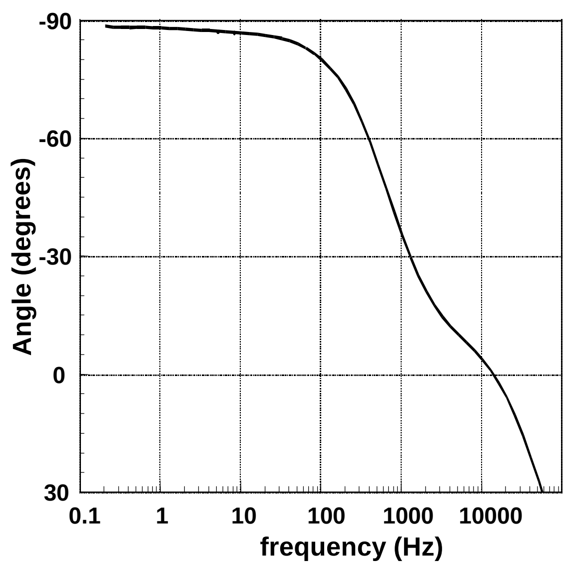


Figure 6. Phase Angle vs. Frequency for a 54 V, 18 mF tantalum Hybrid capacitor.



seconds, ΔV is the capacitor voltage change, I is the current and R is the capacitor resistance in ohms.

An electrochemical capacitor cannot usually be adequately represented as a simple R C circuit because these capacitors have pronounced non-ideal behavior. A better approximation of electrochemical capacitor performance is a 'transmission line' model containing several R C elements connected in parallel.[2] Generally, the more of these elements the model contains, the better the approximation. Nevertheless, the behavior of the Hybrid® capacitor is very ideal compared to other types of electrochemical capacitor, and the simple R C circuit is a sufficiently accurate model. Of course, if greater accuracy is needed, a more complex model could be used.

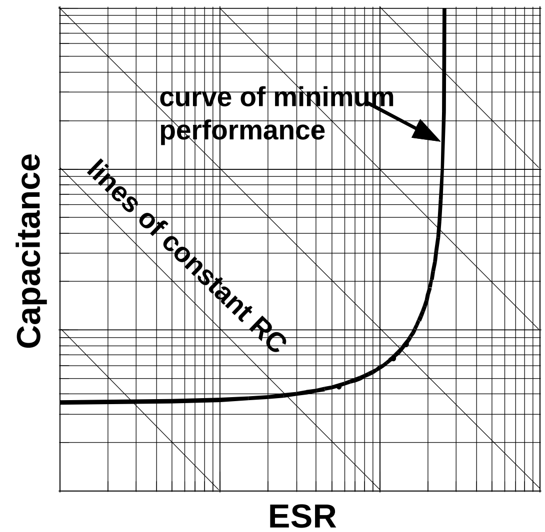


Figure 7. Log-Log Capacitance vs. ESR plot for the ideal RC model. Capacitors which coordinates fall above and to the left of the curve of minimum performance will work in the application.

For every application defined by ΔV, I, and t, there exists a function which defines the minimum resistance / capacitance combinations which can meet the required load profile. A device will meet the required profile if the capacitance is 'above the line' at the point of that device's ESR.

By plotting competing technologies on these charts, one can compare the relative efficiency of one technology over another. For example, applications requiring fast discharge times will require far more capacitance if a device's ESR is high. High capacitance may be problematic for the user because the capacitor will need to be charged before each use, and charge time is proportional to the capacitance.

The position of a capacitor's ESR and capacitance coordinates, plotted with the curve of minimum performance can also be of importance. All electrochemical capacitors rely on an electrolyte to carry current. The resistance of these electrolytes can vary significantly within the operating temperature ranges of typical commercial applications. As can be seen in Figure 11, a device with higher ESR (the Capattery) could lie adjacent to the vertical portion of the minimum performance curve. The performance of such a capacitor may be forced below the curve when a relatively modest increase in ESR (due to low temperature) is factored in. Conversely, low ESR devices reside near the horizontal portion of the curve. ESR changes in this

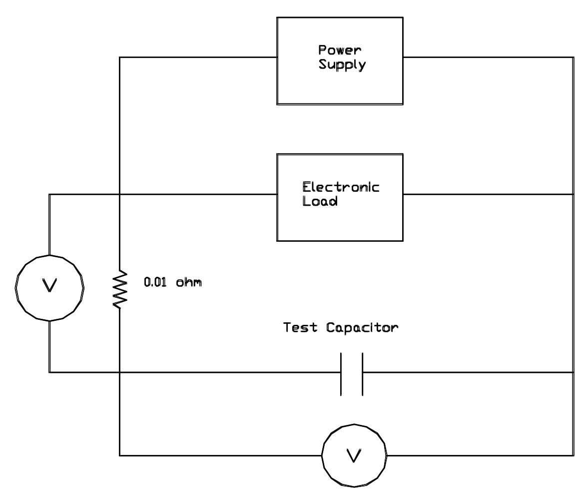


Figure 8. Diagram of the circuit used to measure capacitor performance.

region are not as not nearly as likely to push the capacitor out of specification.

Another useful aspect of these charts, is that lines of constant RC product appear as straight diagonal lines, as shown in Figure 7. By intersecting these lines with the minimum performance curve, the minimum capacitance required for any given electrochemical capacitor technology can be determined. The following examples will use the above techniques to analyze some real-world commercial and military applications.

Measurement Circuit

Figure 8 is a schematic of the circuit used to evaluate capacitor performance in the following examples. Charging power was provided by a HP E3616A power supply. The capacitors were discharged into a Kikusui programmable electronic load, model PLZ153W. This unit was capable of providing a pulsed constant power, constant current, or constant resistance load. A National Instruments model AT-MIO-16E-10 plug-in board residing in a Windows based PC was configured to display and record capacitor voltage and current.

Example Applications

One of the most important potential commercial applications of electrochemical capacitors is in portable digital wireless communications equipment. For example, many terrestrial cell phones and some new satellite phones are now utilizing TDMA transmission protocols. (TDMA stands for time division multiplex algorithm.) In simple terms, these "digital cellular" systems convert the voice signal into numerical data, compress that data, and then transmit it in a continuous series of short pulses.

TDMA protocols often utilize a duty cycle on the order of 10%. The pulsed nature of these digital transmissions generally leads to a pulsed load on the phone's battery. Placing a capacitor in parallel with the battery allows the

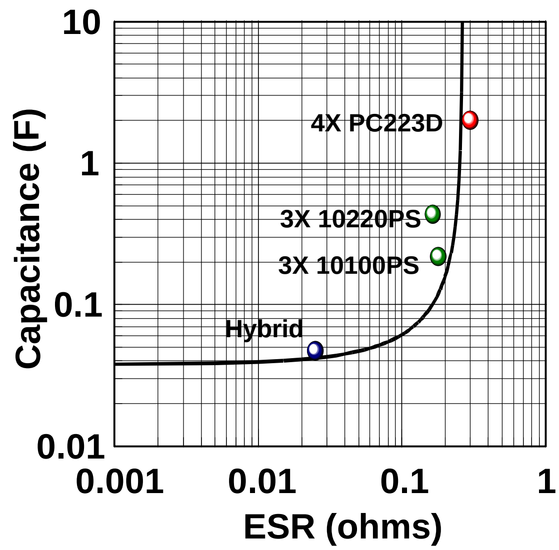


Figure 9. Plot of minimum performance for capacitors in the TDMA-GSM cell phone application. The Hybrid capacitor has a rating of 45 mF, 8 V. The other points plotted are from published data for competing non-aqueous electrochemical capacitors, series-connected (3X or 4X)to provide 8 V operation.

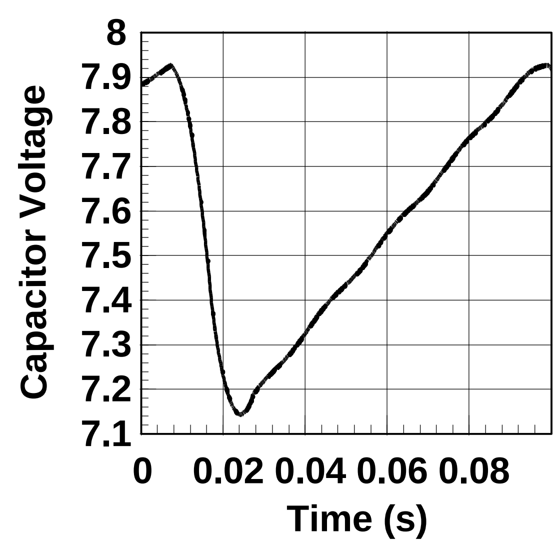


Figure 10. Voltage vs. time for a 45 mF, 8 V tantalum Hybrid capacitor supplying a 3.8 A , 10 ms pulse at a repetition rate of 11 Hz.

capacitor to provide the pulse energy during the 10% transmission time and then be recharged during the remaining 90% of the cycle. Using a capacitor in this way greatly reduces the peak load on the battery. (It should be noted that the lower the ESR of capacitor relative to the ESR of the battery, the more efficiently the capacitor will provide the pulse loads.) Reducing the pulse load on the battery allows it to operate much more efficiently and thereby greatly increases the total "talk time" of the system.[3]

Satellite phones use particularly powerful TDMA pulses to penetrate the atmosphere and reach satellites which may be over a thousand miles away from the handset. The higher power capabilities of the Hybrid® capacitor make it an excellent power source for these pulse requirements. A typical satellite phone pulse requirement is:

Pulse current: 3.8 Amps
Pulse time: 10 ms
Operating Voltage: 8 volts
Max delta V: 1.0 Volts
Repetition rate: 11 Hz

As shown in Figure 9, the necessary capacitance for this pulse profile becomes much higher with increasing ESR. Capacitors with ESR greater than about 200 mΩ cannot meet the requirement regardless of how much capacitance they might possess. If the constant-RC lines are plotted, it is possible to determine the amount of capacitance required for various electrochemical capacitor technologies to meet the requirement. Values of 1 and 0.1 seconds have been assumed as typical RC constants for carbon and bi-polar ruthenium capacitors respectively. A conservative value of 0.002 seconds was used for tantalum Hybrid technology. As is shown in figure 9, the carbon devices would require over 4 farads, and the bi-polar ruthenium devices would require at least 450 mF. However, the tantalum

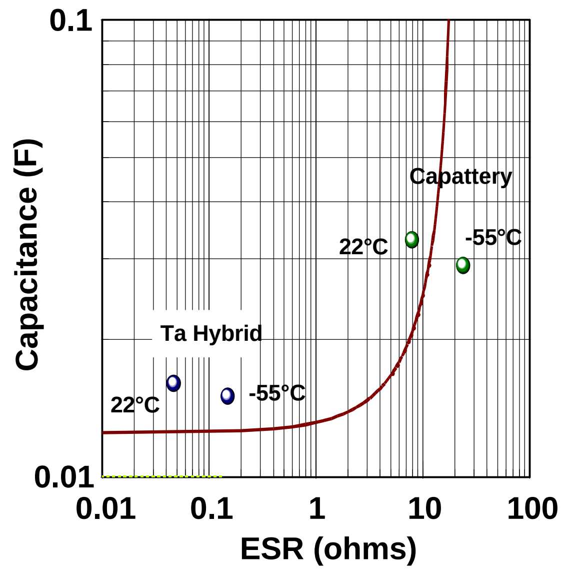


Figure 11. Curve of minimum performance for the missile fuze application. Note that the increase in Capattery ESR at -55°C forces its performance below the curve, whereas a similar percentage change in Hybrid capacitor ESR has little effect on overall performance.

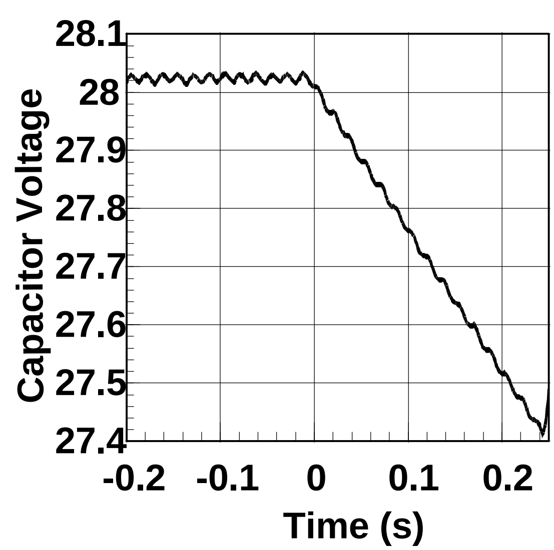


Figure 12. Voltage vs. time for a 17 mF, 28 V tantalum Hybrid capacitor in the missile fuze application. Current pulse is 0.05 A.

Hybrid capacitor, only requires about 40 mF. Figure 10 shows measured voltage vs. time data for a 45 mF, 8 V Hybrid® capacitor driving the TDMA mobile phone load described above.

If temperature-induced variation in resistance is also included in the analysis, the differences become even more distinct. An application demonstrating the importance of low temperature ESR increase is in a fuze circuit powering an advanced penetrator weapon. Here, the capacitor must accept a charge after the weapon is deployed (typically during flight), reach operating voltage in <10 s, power the electronic control package and provide power to detonate the explosive. Consistent with state-of-the-art weapon design, the capacitor must have high energy density because decreasing the mass increases the likelihood of the capacitor surviving multiple severe mechanical shock loads. The unit must also perform in a low temperature environment. This example is used to illustrate the differences in performance exhibited by a Hybrid® capacitor and a Capattery® carbon-sulfuric acid electrochemical capacitor. The physical size of the two units under comparison is identical.

Pulse current: 0.05 Amps
Pulse time: 250 ms
Operating Voltage: 28 volts
Max delta V: 1.0 Volts
Repetition rate: Single Pulse
Charge Current: 0.15 A
Charge time: < 10 s

Figure 11 shows the curve of minimum performance for this application, and it predicts that the Capattery at -55°C would fail to meet the performance requirement. Measurements confirm that the Capattery voltage drop is greater than one volt and the full charge voltage is not reached in the 10 s allowed. Figure 12 gives voltage measurements for a 17 mF, 28 V Hybrid® capacitor subjected to the missile fuze load profile above.

CONCLUSION

These examples illustrate that, for applications which require short pulse times (e.g. < 50 ms), low RC time constants allow tantalum Hybrid® capacitors to supply the required pulse power with a far lower capacitance device. Furthermore, the tantalum Hybrid capacitor's low ESR allows it to be far less sensitive to temperature related ESR changes. These can be very important to the OEM equipment designer who must size a capacitor so that it will function adequately at all points within operational ranges specified for the equipment in question. In most pulse applications, a limited current is available to charge the capacitor. For this reason, lower capacitance is of great value to the designer because less time is required to charge the capacitor before use. This charge time can be a significant operational requirement. Cell phone users do not want wait ten minutes for their phone to 'warm up' before placing a call. Weapon systems have a limited flight time in which to charge the capacitor.

In summary, the extraordinarily low RC time constant of the tantalum Hybrid capacitor technology enables it to provide pulse power more efficiently than devices with orders of magnitude greater capacitance. As long as the pulse requirements are met, lower capacitance is an advantage because less time is required to charge the capacitor before use.

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