Hybrid Capacitors with High Specific Power

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Electrochemical energy storage devices employ two types of electrodes that differ in the way they store charge. One kind on which electrochemical reactions with the electrolyte occur during charging or discharging has come to be known as faradaic electrode. The other one stores charge without chemical reactions and is non-faradaic. Batteries have a pair of electrodes that store energy by a chemical process. Electric double layer capacitors, electrolytic capacitors, and electrostatic capacitors all store charge physically.

Faradaic charging always involves transfer of electrons between an electrode and an electrolyte. It also requires a mass transfer of ions or atoms at the electrodes. This is the root cause of most disadvantages associated with chemical rather than physical charge storage. Faradaic electrodes have much higher specific energy but suffer in the areas of speed, repeatability, and life. Electrochemical reactions are indeed very slow compared to moving physical charge on a surface, and are subject to limitations imposed by the electrolyte which conductivity decreases with temperature. This explains the generally poor performance of batteries at low temperatures and their low specific power compared to capacitors at any temperature. Repeating charge cycles induce chemical and physical changes to the electrodes that are not quite reversible. So often the life of a battery is measured in hundreds or thousands of cycles. Overall life and shelf life is limited because of parasitic irreversible electrochemistry. The capacitance of faradaic electrodes is often proportional to the electrode volume. Faradaic devices have the highest specific energy, but are limited in operating voltage to the electrolyte breakdown potential.

Non-faradaic charging is a physical charge storage mechanism that suffers none of those problems. Electric current causes no physical change in a conductor. In the ideal case, there are no physical changes and no wear-out mechanisms. The cycle life of electrostatic and electrolytic capacitors is virtually unlimited. Electronic conduction is fast and for the purpose of electrostatic capacitors, independent of temperature. Electrochemical and electrolytic capacitors do have an electrolyte, which has conductivity temperature dependence, a function of the variable speed of ionic charge transfer in a liquid electrolyte, which properties depend on temperature. The capacitance of non-faradaic electrodes is proportional to electrode surface area. The specific capacitance is orders of magnitude lower compared to faradaic electrodes.

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A hybrid capacitor (US Pat. 5,369,547) combines a high surface area non-faradaic electrode with a faradaic electrode and a compatible electrolyte to form cells, which tend to maximize the best features of each. Hybrid capacitors are asymmetric and thus correct polarity must be observed. The capacitor described in the patent has a faradaic negative electrode comprised of ruthenium oxide, sulfuric acid electrolyte, and a non-faradaic positive electrode, tantalum pentoxide coated tantalum metal. The negative electrode has a large capacitance and the positive electrode has a high voltage dielectric. The positive electrode has an unlimited cycle life and is responsive to alternating current. The hybrid capacitor has about 4X higher energy density compared to an equivalent electrolytic capacitor.

Hybrid capacitors are designed to optimize the voltage at each electrode. The charge is proportional to the capacitance and voltage, and since the two electrodes are in series a charge of equal magnitude exists on both.

$$C_1V_1 = Q = C_2\,V_2$$

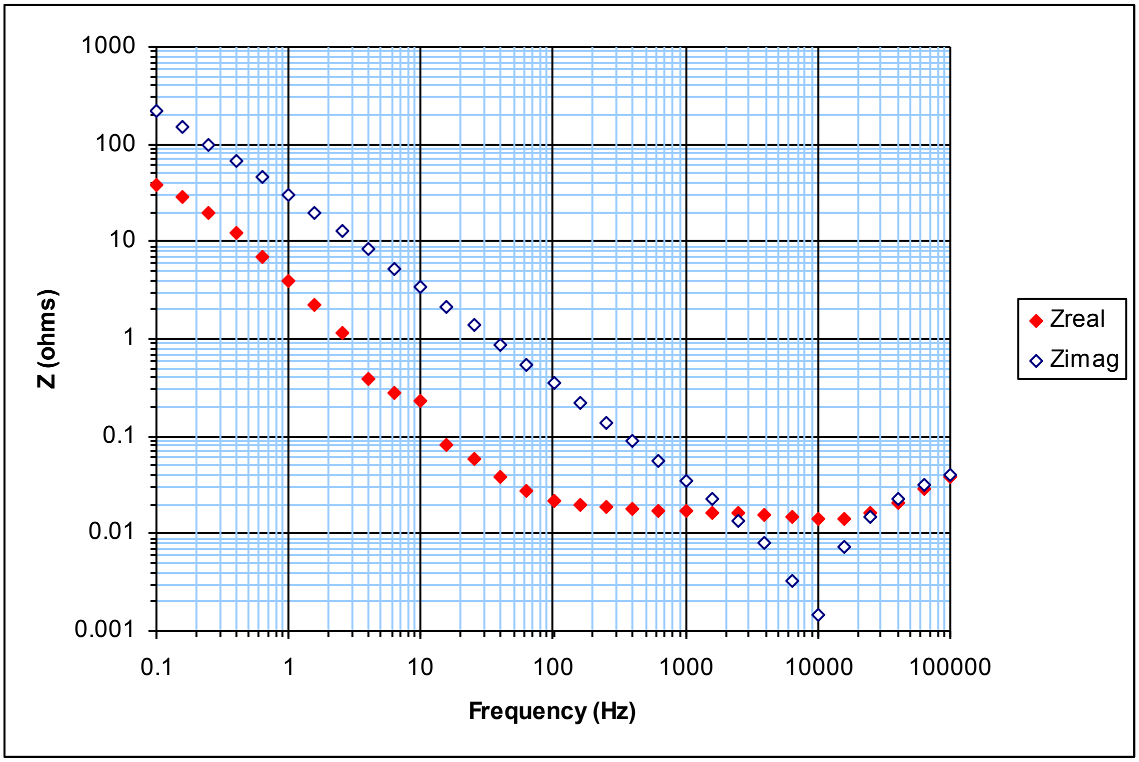
Electrodes are sized to avoid the possibility of exceeding the electrolyte breakdown potential at the negative (faradaic) electrode. In a typical tantalum hybrid capacitor, the negative electrode capacitance is at least 100 times greater than the overall capacitance and its voltage 100 times less. Accordingly, the voltage on the non-faradaic positive electrode is much higher and the use of a dielectric prevents electrochemical reactions at that interface.

Because hybrid capacitors can have a high cell voltage, the necessity of series connections is eliminated or greatly reduced. Among obvious advantages, such as greatly facilitated assembly, a single high voltage cell has lower resistance than a stack of symmetric cells. This is important to power performance as power is indirectly related to the resistance. Capacitors with high specific power are needed for a variety of applications with repetitive high current pulse discharges. Using a capacitor, the primary power source can be sized to the average power, saving cost, space, weight, and increasing reliability while improving performance.

Tantalum hybrid capacitors are designed for demanding applications requiring long life, wide temperature range, reliability, high specific energy and power. The hermetic design fits the expectations of customers involved with military or aerospace applications. The design has continued to evolve over the past 10 – 15 years and the latest version has considerably increased specific power. The capacitors have high specific energy compared to electrolytic capacitors and higher specific power.

Figure 1 below is a plot of the impedance of a TDD3125452 capacitor rated for 4500uF at 125 volts. Zreal (z’) is the resistance. Zimag (z”) is the reactance. This capacitor has an ESR, taken at 1kHz, of 17mohm.

Figure 1.



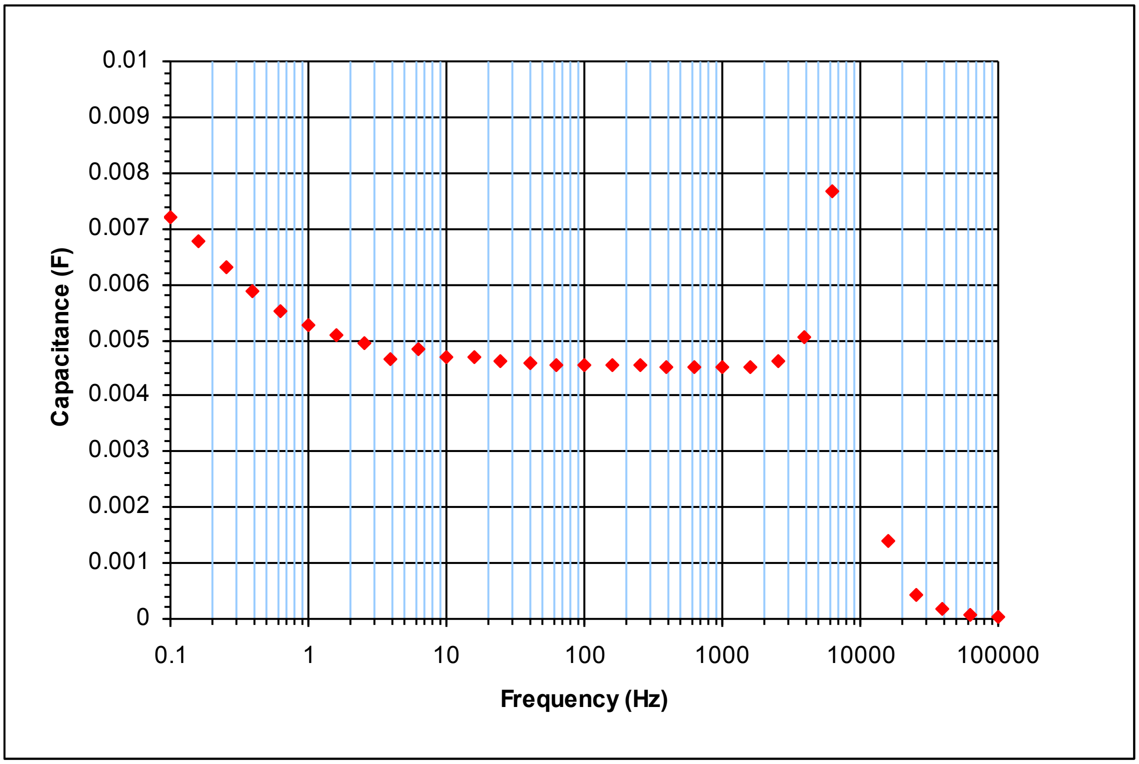


Figure 2. Capacitance of a TDD3125452 capacitor. The steep rise above 3kHz is a value at the resonance frequency and is anomalous. The resonance frequency is about 7kHz.

The capacitance was derived from z”, the reactance, according to

$$C = 1/(2 P f z'')$$

where f is the frequency. The energy stored in a charged capacitor is directly related to the capacitance by

$$E = \tfrac{1}{2} C V^2 \qquad \text{eq. 1}$$

and the power is proportional to 1/R according to eq. 2,

$$P \propto V^2/R. \qquad \text{eq. 2}$$

$$P = V^2/4R \qquad \text{eq. 2a}$$

Plotting capacitance over 1/R yields Figure 3.

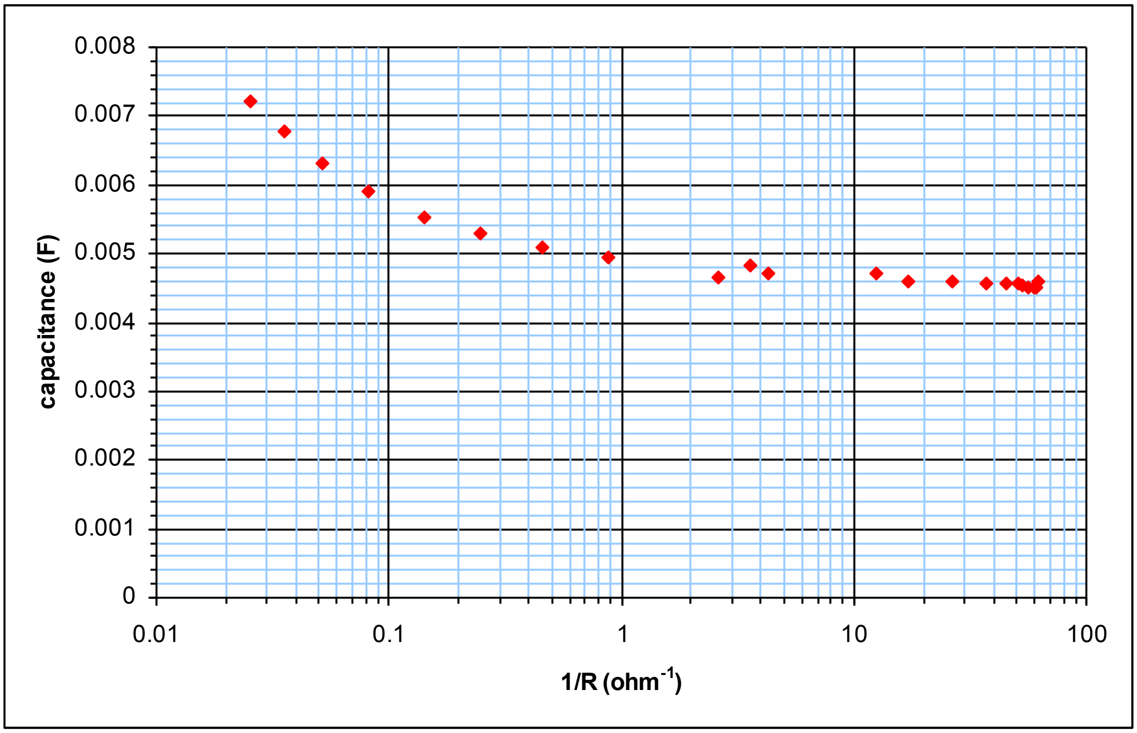
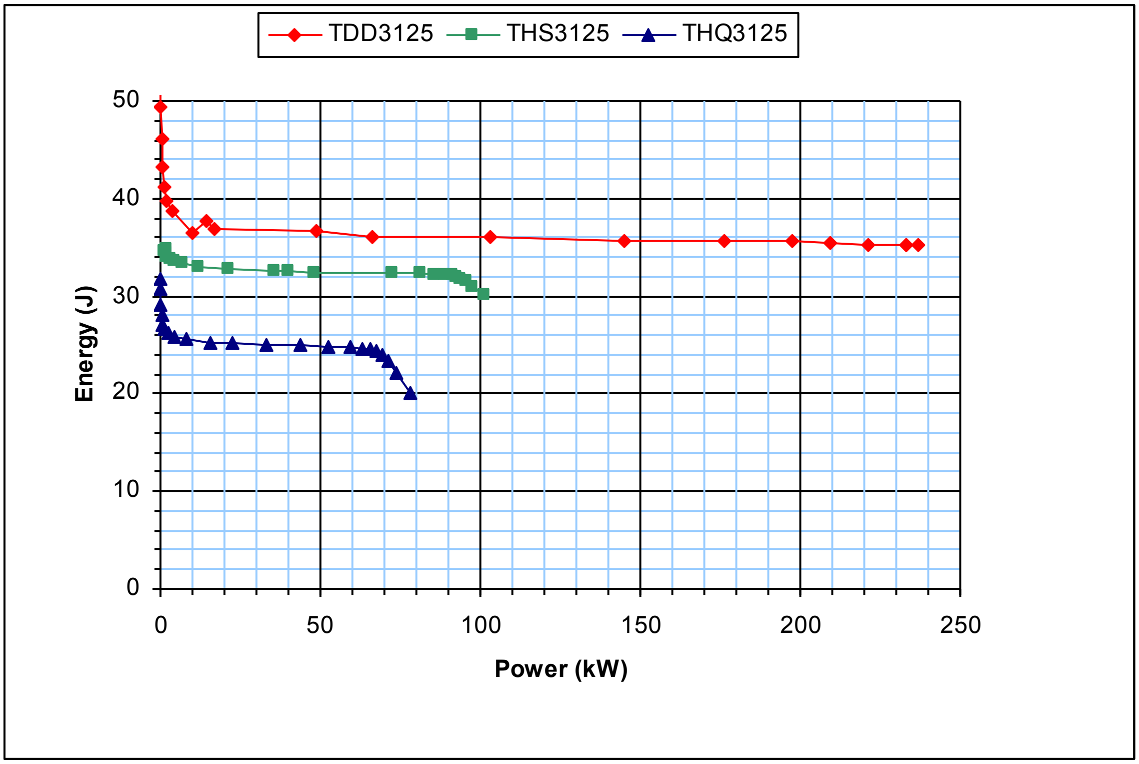


Figure 3. Plot of capacitance vs. 1/R with the values to the right of resonance removed.

The proportion in eq. 2a, can be understood to lie in the circuit that uses the capacitor. Capacitors can deliver maximum power into a load having equal resistance to the capacitor ESR. So eq. 2 becomes $P = V^2/ 2 R$. However, this is not practically the case. A more conservative estimate of power in a practical device drops this a factor of two, so power is $P = V^2/ 4 R$ is used here. Making V = 125 volts from eq. 1, E = 7812.5 C. Similarly, at V = 125 volts in eq. 2a, P = 15625 / 4 R. Doing the arithmetic results in the Ragone diagrams shown below.

Figure 4. Energy vs. Power for a single capacitor as noted. The newest TDD3 type has higher energy and power. THS3 and THQ3 are older models.



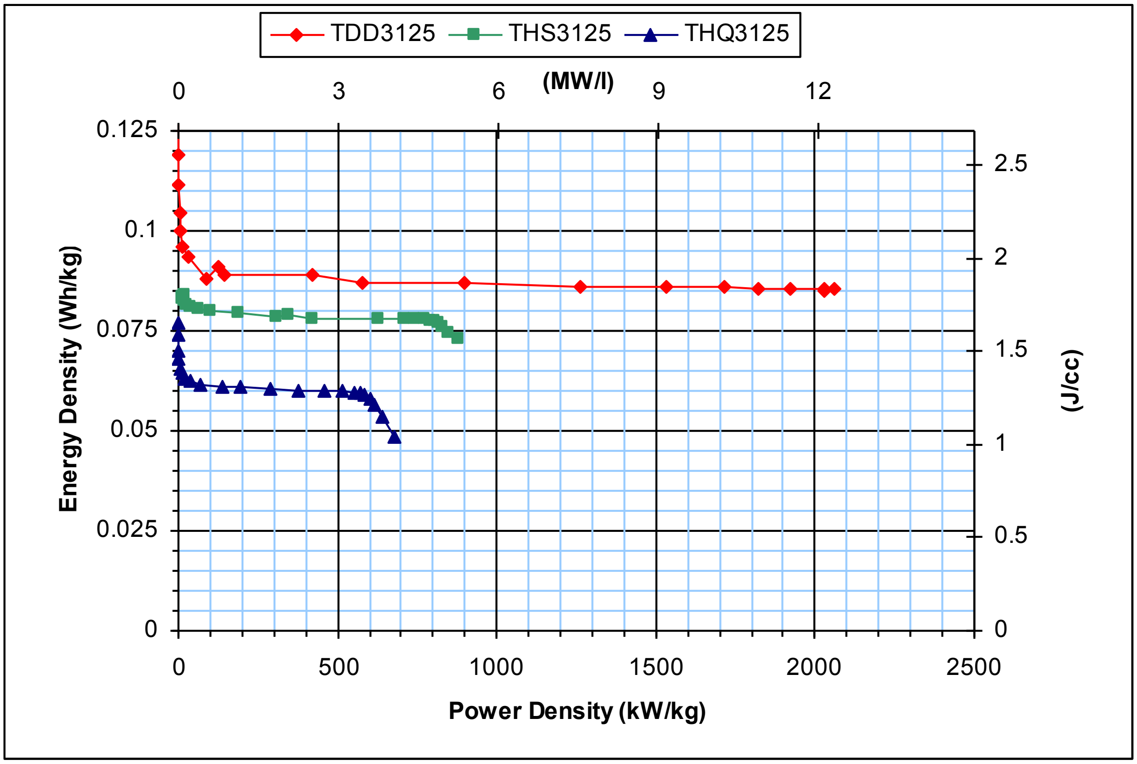


Figure 5. Energy vs. power for TDD3 in three different voltage ratings. The energy of the lower voltage TDD models are similar to the THS or THQ but the power is higher.