Effect of Time Constant on Power Capability of Supercapacitors

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Supercapacitors are now being used in a number of applications, mostly as low power devices for memory backup purposes. It is expected that as supercapacitors move into other applications, higher and higher power densities will be required. One of these applications is for load levelling in hybrid electric vehicles. Indeed some work has already been undertaken in this area. Another high power application is in telecommunications, where short high power pulses are required. This move to high power will continue, and it is desirable to establish some capacitor specific testing procedures that will enable a valid comparison between different capacitor technologies.

Compared to batteries, supercapacitors can be described as high-power, low-energy, energy storage devices. Supercapacitors are often compared on an energy density basis, however energy density is not a useful comparison under high power conditions, as shown below. Power density alone, is also not very informative since it provides no information on the amount of work a capacitor can do. Whilst Ragone plots have been used to characterise batteries for many years, capacitors have very different characteristics and their behaviour is not always best described using Ragone plots. One noticeable difference is that the power capability of a supercapacitor depends on its state of charge, in contrast to batteries (Pell & Conway, 1996). Another is that capacitors may be required to be charged, as well as discharged, at high power. Here we propose an alternative test for capacitor capability, called a power capability chart, (PCC), which combines energy and power density and provides a tool for clear discrimination between supercapacitors of different characteristics.

A traditional Ragone plot describes the relationship between energy and power, generally with the assumption of the capacitor voltage dropping to V/2 (ie using three quarters of the energy), and power delivered into a matched load (load resistance equal to capacitor esr). The energy dissipated in the capacitor depends on the current, and so also on the power level. In many applications however, the load resistance will change depending on the power required, and in many circumstances constant power delivery is required. In our approach we propose constant power delivery, and this is modelled below.

The behaviour of an ideal capacitor under constant power charge and discharge can be calculated.

The basic equations are:

$$\begin{aligned} Q &= CE \\ V &= E - iR_{esr} \\ P_{del} &= iV \\ i &= -\frac{dQ}{dt} \end{aligned}$$

where C is capacitance in Farads, E is the capacitor emf, V is the terminal voltage of the capacitor, i is the current, P_{del} is the power delivered to the load and Q is the capacitor charge at time t. Using the

DC time constant, $\tau_c = CR_{esr}$, these equations can be rearranged to

$$\frac{dQ}{dt} = \frac{1}{2\tau_c}\left[\left(Q^2 - 4C\tau_c P_{del}\right)^{\frac{1}{2}} - Q\right]$$

The solution to this equation, given an initial charge Q, provides Q at time t, which then allows calculation of i, E and V. When

$$Q^2 = 4C\tau_c P_{del}$$

there is insufficient charge to provide P_{del} and this time is referred to as the breakpoint. The charge remaining in the capacitor from this point onwards can be calculated using

$$\frac{dQ}{dt} = -\frac{Q}{2\tau_c}$$

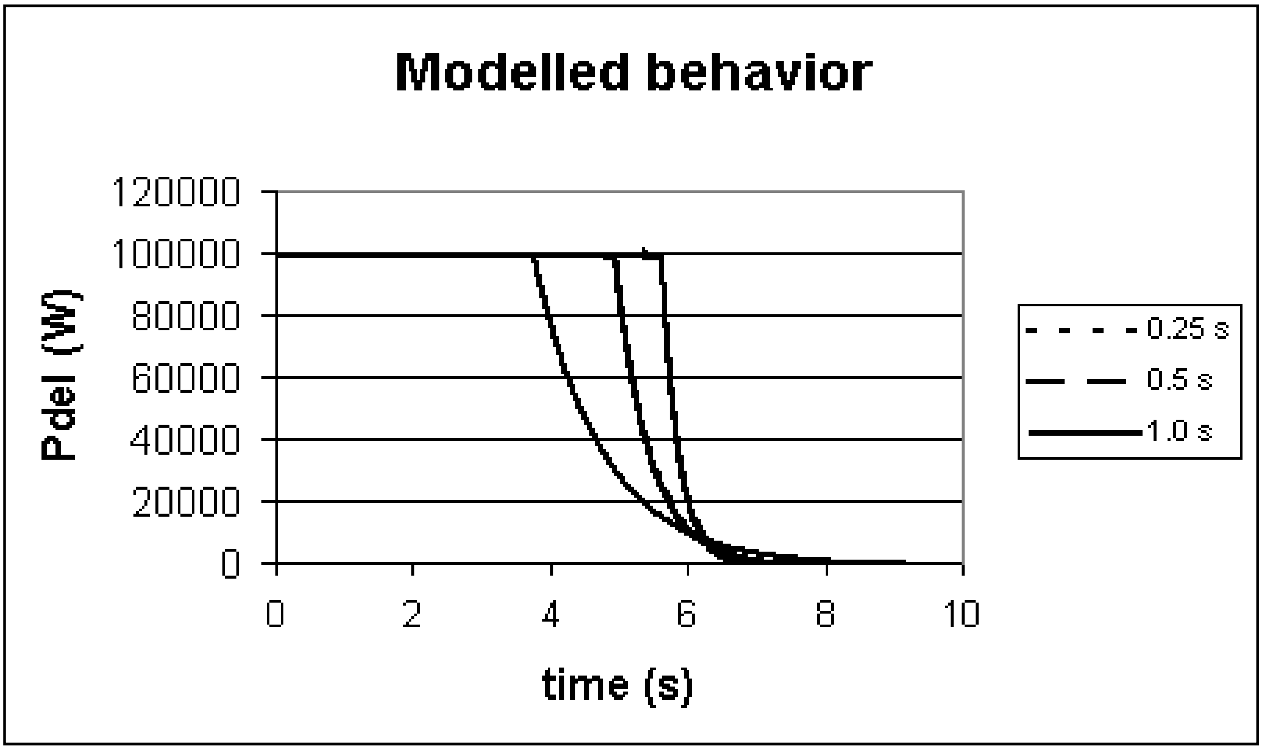

Figure 1. Effect of time constant on 100 kW power delivery

An example of a PCC is given in Figure 1. In this example, 3 capacitors of time constant 0.25, 0.5 and 1.0 s are compared at a discharge power of 100 kW (P_{del}). If a value of 90 kW is taken as the cut-off point it is apparent that the 1.0 s time-constant capacitor can only deliver power for 4 s, while the 0.25 s time-constant capacitor can deliver power for 5.6 s, a 40% increase in useful work. All capacitors store the same amount of energy. This behaviour is expected from a traditional Ragone Plot, with the low RC capacitor extending to higher power densities.

The % losses are shown in Figure 2 and although not obvious from this Figure, the dissipated energy increases monotonically with time constant as pointed out by Miller (1997) for variable power charge/discharge cycles.

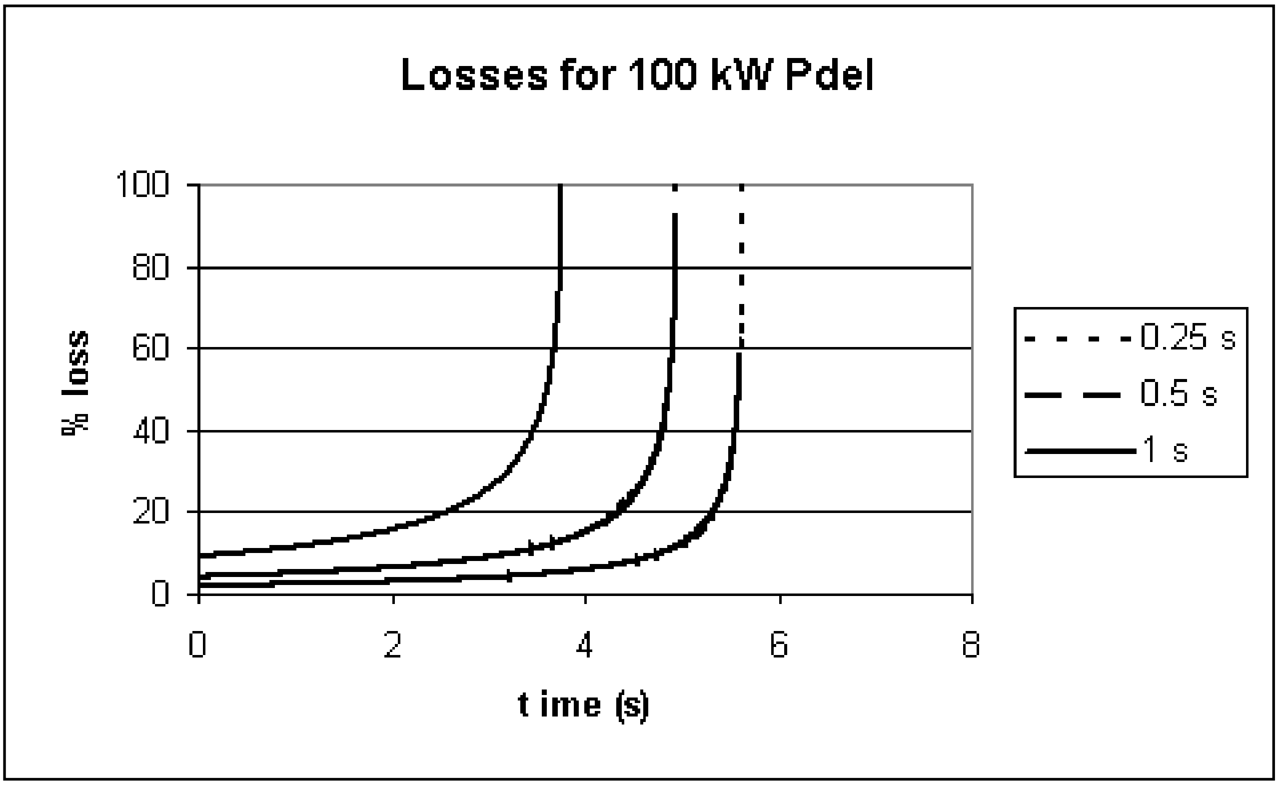

Figure 2. Effect of time constant on supercapacitor losses

Constant power charge is also usefully plotted, and when combined with the discharge data, can be used to estimate total losses. Incorporating a time delay between the charge and discharge curves allows the effects of distributed capacitance and leakage to be determined.

Practical measurements of power capability are relatively straightforward, provided the equipment is available. The data in Figures 3-5 have been obtained on a commercially available 9 F capacitor with a time constant of 0.6 s (DC values) charged to 2.0 V.

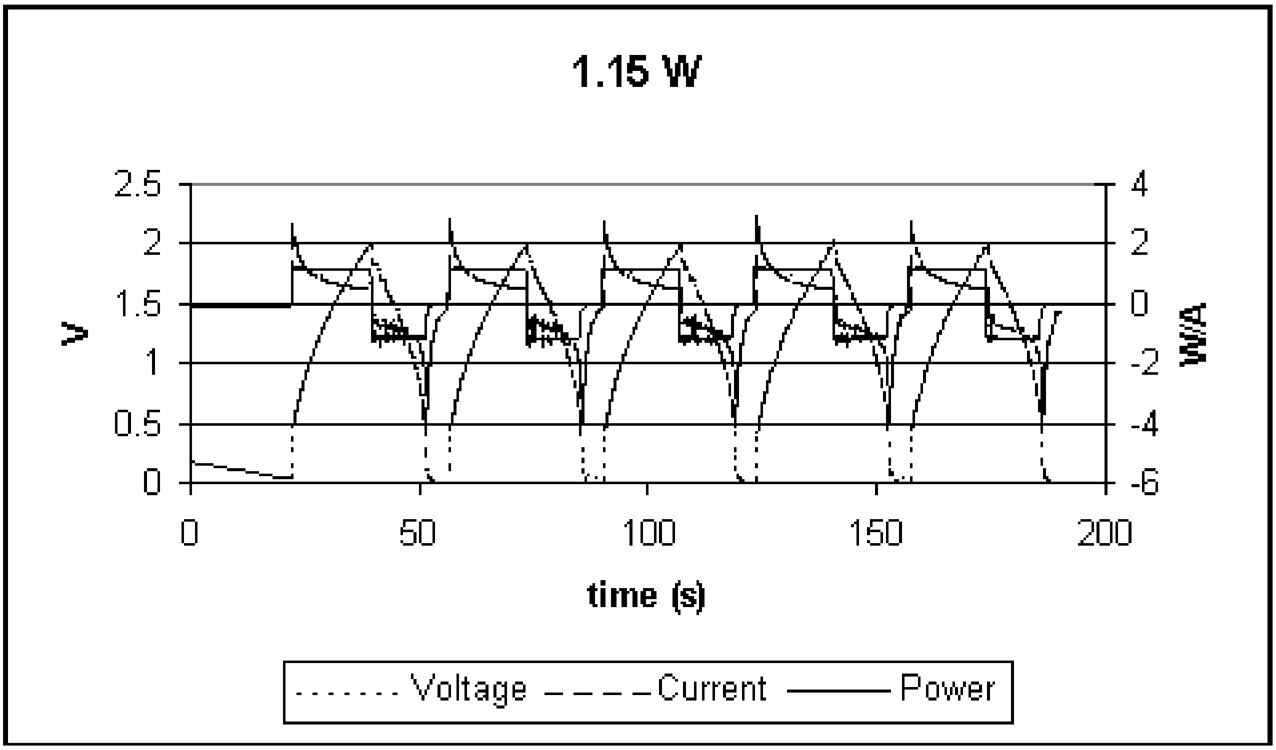

Figure 3. Voltage, current and power during constant power cycling at 1.15 W

The procedure is to charge the capacitor from 0 volts at the desired power level until the rated or chosen voltage is reached, at which time the polarity of the charge current is reversed and the capacitor discharges at constant power until the level cannot be sustained, and then at maximum power achievable, which corresponds to a matched load. This is maintained until 0 or a pre-defined voltage is reached. Alternatively, the discharge cycle can be terminated once the requisite power is no longer available and the charge cycle resumed. In either case, the process is repeated for 2 full cycles and the measurements are taken from the third cycle.

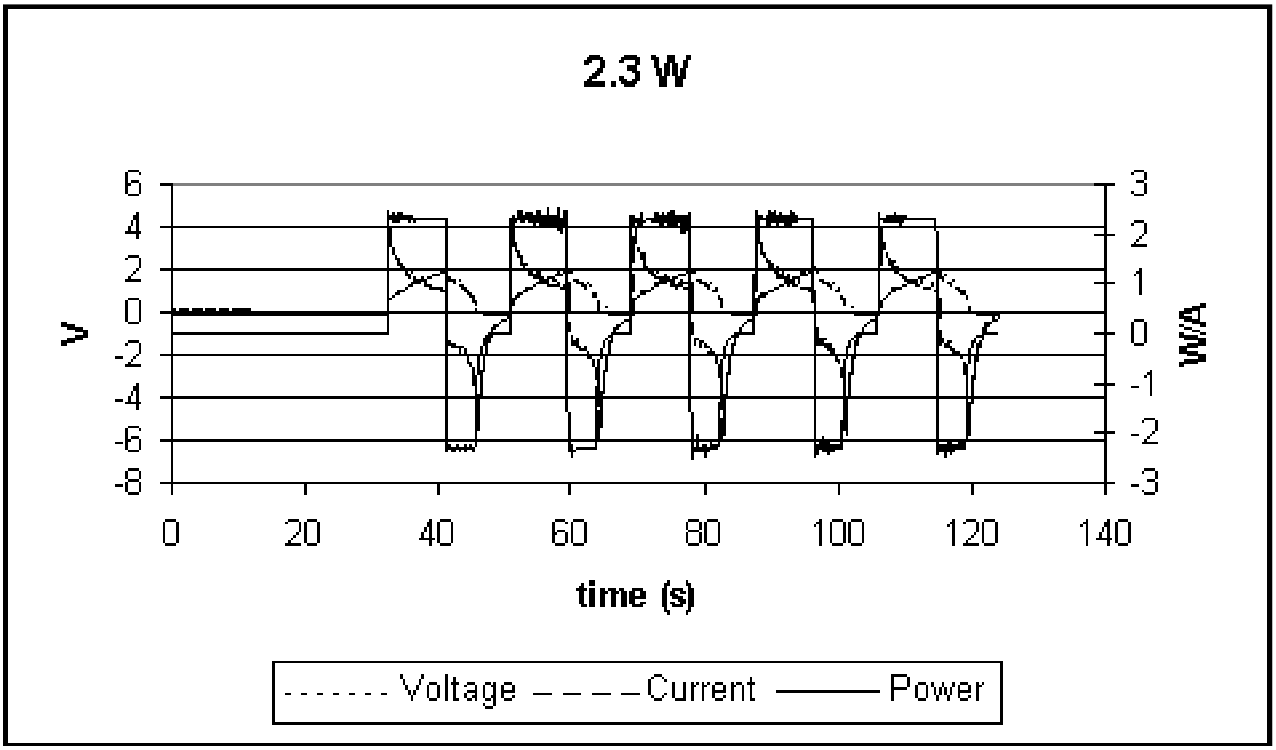

Figure 4. Voltage, current and power during constant power cycling at 2.3 W

It is apparent that as the power levels increase, the ratio between discharge power time and charge power time decreases. At a power of 6 W (952 W/kg) insufficient charge is stored under these conditions to provide more than a fraction of a second of power at the same level in discharge. The energy provided during charge and extracted during discharge is easily measured as the power-time product. A summary of the salient characteristics is given in Table 1. The time period, t, is the width of the charge or discharge curve taken from when the power reaches 90% of the charge power to 90% of the discharge power.

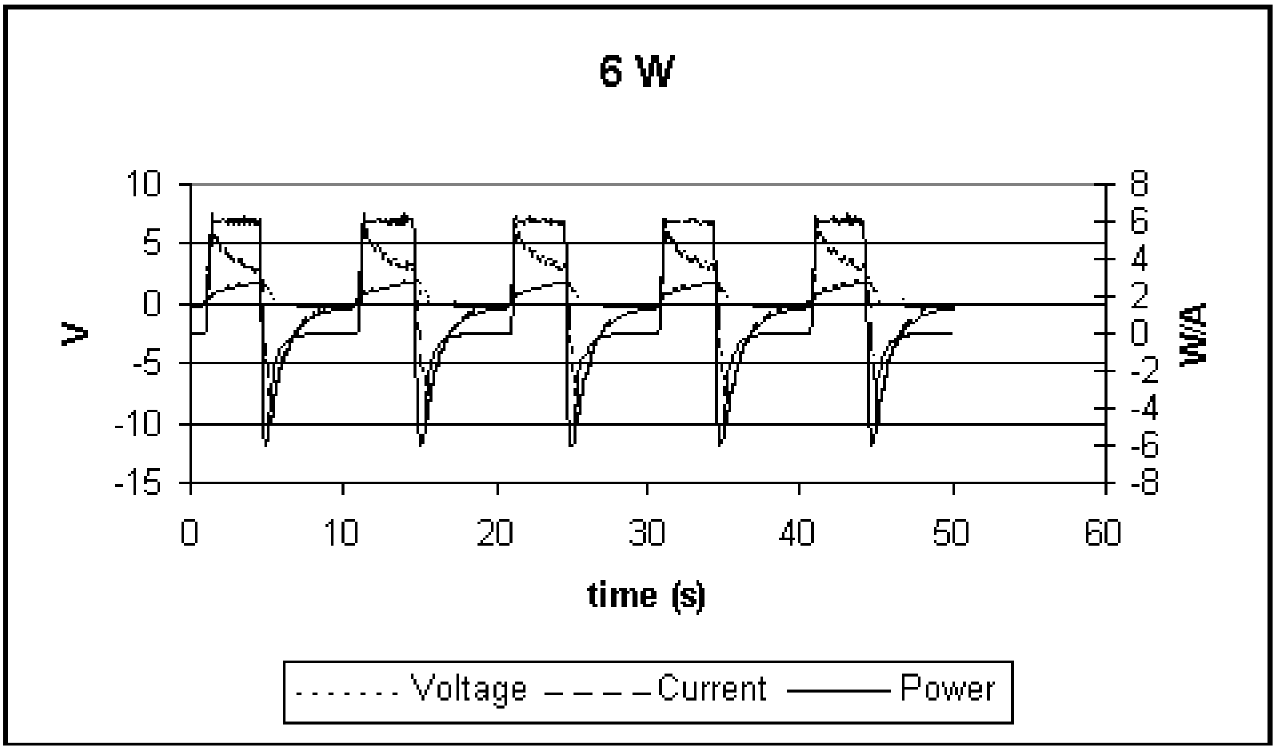

Figure 5. Voltage, current and power during constant power cycling at 6 W

The energy density under charge is seen to be invariant with power, however this reflects the energy provided to the capacitor, and not the energy actually stored. This interesting characteristic is a consequence of operating in the constant power mode where the energy density is actually defined by $0.5CV^2$. The recoverable stored energy however is much less and decreases almost linearly with power level.

Table 1. Summary of data from power capability chart

Power		Charge					Discharge				
(W)	W/kg	V max	I min	I max	t (s)	Wh/kg	I min	I max	t (s)	Efficiency %	Wh/kg
0.2	32	2	0.1	1.2	94.4	0.85	0.1	1.5	84.6	90	0.76
1.15	183	2	0.58	2.6	17.2	0.89	0.68	3.7	10.1	59	0.52

2.3	365	2	1.1	3.7	8.3	0.86	1.3	4.8	3.9	47	0.40
6	952	2	2.3	5.86	3.17	0.85	4.7	7.3	0.29	9	0.08

The percent losses during discharge are greater than during charge under the PCC conditions as higher currents are required during discharge to meet the power levels. This effect is compounded with large RC as the stored energy is less, and the IR drop greater, as shown by Miller (1997) for a hybrid electric vehicle simulation.

At low power and room temperature, the simple RC model adequately describes the behaviour of carbon based supercapacitors, however at higher power the effect of distributed capacitance becomes significant and the simple model no longer applies. The power level at which this occurs depends on the time constant of the capacitor. High time constant capacitors show deviation at lower power levels than low time constant devices. The observable effect of distributed capacitance is a decrease in available capacitance at high power levels, and at the beginning of the charge and discharge cycle. The latter effect results in a larger than anticipated voltage drop in the first few milliseconds of charge or discharge. An improved model incorporating distributed capacitance is currently under development.

Conclusions

If supercapacitors are to be used where they provide a clear advantage over batteries, ie under high power conditions, then the effect of time constant is obvious – low time constants are essential to minimise losses and to recover maximum energy. The results of constant power cycling, defined here as a Power Capability Chart provides very good discrimination between capacitors and a clear picture of the energy and power that can be expected during use in real applications.

Acknowledgements

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References

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