PowerRESPONDER® State of Health Measurement

The hybrid-supercapacitor PowerRESPONDER products can demonstrate energy densities much greater than a traditional EDLC device, making them an attractive energy storage alternative. The main difference between these two types of supercapacitors is in the greater potential afforded by the Lithium-ion electrode which results in a slightly non-linear capacitance as a function of voltage (Figure 1). Additionally, the hybrid cell demonstrates a greater deviation in effective distributed resistance (EDR) component from the effective series resistance (ESR) which is important to understand when contemplating remaining energy and state of health.

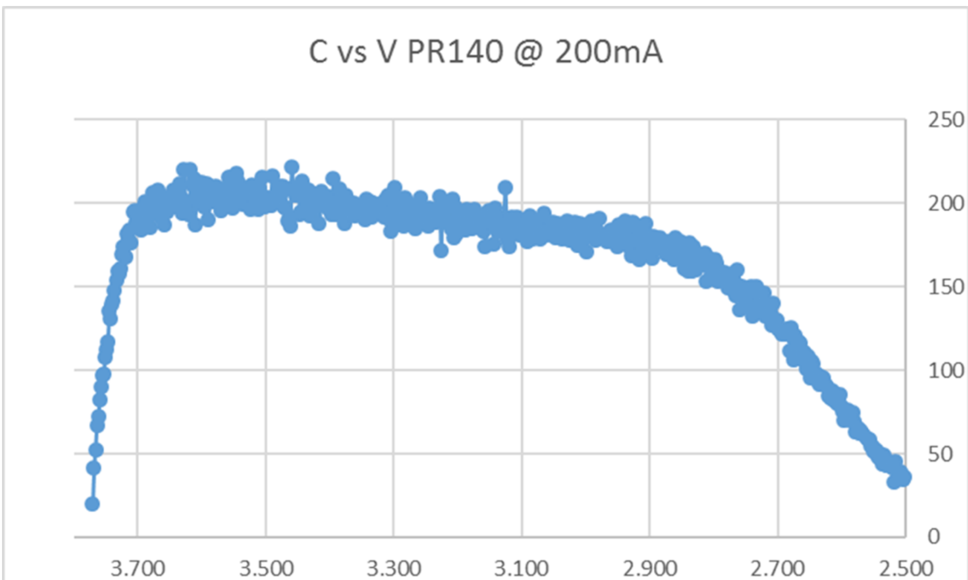

Figure 1. Capacitance calculated by taking voltage measurements over time while discharging a PR140 product at 200mA from an initial voltage of 3.8V.

Parameter Measurement

Below is a graph (Figure 2) which represents the early stage of discharge under a constant current load. On application of the load the capacitor voltage drops almost instantaneously followed by a period where the voltage declines at an exponential rate. Given the equation i=C(dv/dt), a good estimate of initial capacitance is given by i*(t2-t1)/(v1-v2) [EQ1].

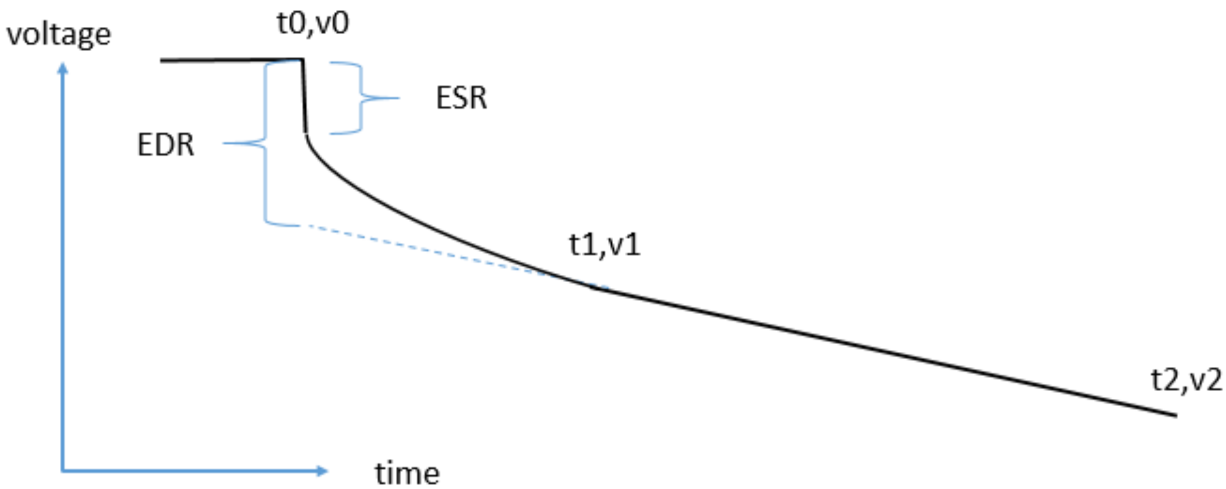

Figure 2. Capacitor voltage profile at onset of constant current discharge

The problem with Equation1 (EQ1) is finding the point in time (t1) when the EDR component becomes the dominant internal loss component such that subsequent voltage measurements will produce a relatively consistent capacitance calculation. One method is to continuously calculate the change in capacitance, dC/C, until it becomes sufficiency small. Additionally, one may simply wait for a period before calculating capacitance.

ESR, or AC ESR called out in our datasheet, is an important parameter regarding power delivery to pulsed loads. In terms of energy content of a capacitor discharged at a continuous rate to empty, as would be the case for many UPS applications, EDR, or DC ESR called out in our datasheet, is more pertinent. From Figure 2 it is seen that ESR is determined by the instantaneous voltage drop on the application of the load divided by the load current. EDR may be determined by projecting the discharge voltage curve back to time t0 from the point where the capacitance measurement has stabilized (t1) and divide by the load current. A note on interpreting Figures 1 and 2: The capacitance is inversely proportional to the derivative of voltage over time; the initial low capacitance value is a transient event resulting from the effects of ESR/EDR; Figure 1 is a plot of Capacitance over Voltage (not time); Figure 2 is a plot of Voltage over time.

Figure 3 shows actual data from a single series (1S) PR140 device charged to 3.8V and discharged at various currents. The measurements are performed on sweeps of voltage measurement resolution (from 2mV to 8mV) and test current (from 50mA to 200mA). The object is to measure capacitance and EDR at full charge using the least amount of energy as would be required for a mission critical UPS in the determination of state of health.

2mV resolution	**convergence: dC/C iir 0 or change sign**		
test current (A)	0.05	0.1	0.2
capacitance measured	190	175	168
time to convergence	102	49	34
voltage at convergence	3.761	3.75	3.719
capacitance at 250sec	196	197	207
energy required @ convergence(J)	23	23	32

4mV resolution	**convergence: dC/C iir 0 or change sign**		
test current (A)	0.05	0.1	0.2
capacitance measured	192	191	198
time to convergence	189	103	197
voltage at convergence	3.739	3.722	3.674
capacitance at 250sec	197	198	209
energy required @ convergence(J)	39	45	71

8mV resolution	**convergence: dC/C iir 0 or change sign**		
test current (A)	0.05	0.1	0.2
capacitance measured	197	186	197
time to convergence	249	56	99
voltage at convergence	3.724	3.695	3.652
capacitance at 250sec	197	200	216
energy required @ convergence(J)	51	63	86

Figure 3. PR140 capacitance measurement data. Data taken at high resolution and recorded at resolutions of 2, 4 and 8 mV.

The term convergence in Figure 3 means that the measured change in capacitance has stabilized over time (dC/C=(C(n)-C(n-1))/C(n)=0) [EQ2] which indicates that the ohmic loss in the cell has stabilized. Contrary to the literature, the Figure 3 data indicates that discharge at higher rates doesn't accelerate convergence to a solution noting that it takes about 200 seconds for the EDR to stabilize for all cases.

To recount the measurement process:

1. Capacitance (C) = the discharge current (i) * the change in time (e.g. t2-t1) / the change in voltage (e.g. v1-v2): this produces valid data once dC/C = 0. The process involves taking voltage measurements and calculating dV/dt (see EQ1&EQ2). * Filtering (averaging) of data and calculations, using formulas such as y(n)=0.5x(n)+0.5y(n-1) [EQ3], may be necessary (particularly regarding derivatives such as capacitance) to a degree given that it is understood that averages and courser resolution delay the results and therefore consume more energy to determine the desired result.
2. ESR (AC ESR) = the instantaneous change in voltage / discharge current [EQ4]
3. EDR (DC ESR) = the cell voltage before discharge (v0) – the change in capacitance under load over time (v2 + (t2-t0)*i/C) [EQ5]

Voltage Compensation

The hybrid devices are rated in farads but due to device non-linearity the capacitance measurement will differ as a function of voltage. The rated value CAP of the device, further termed capacity, is derived by measuring the energy delivered to a load (E) during constant current discharge (I):

E = ½ CAP ((Vfull-I*EDR)^2 - Vempty^2) [EQ6]

In the case of the PowerRESPONDER® product datasheet parameters: Vfull = 4 Volts; Vempty = 2.5 Volts; I = nominal current; EDR = DC ESR. From Figure 1 it is observed that the measured C for 4 Volts is greater than that for 3.6 Volts. The capacity rating is equivalent to a linear capacitance when charged or discharged from full to empty. Figure 4 provides a correction guideline for use of CAP as a linearized capacitance for values below 4 Volts.

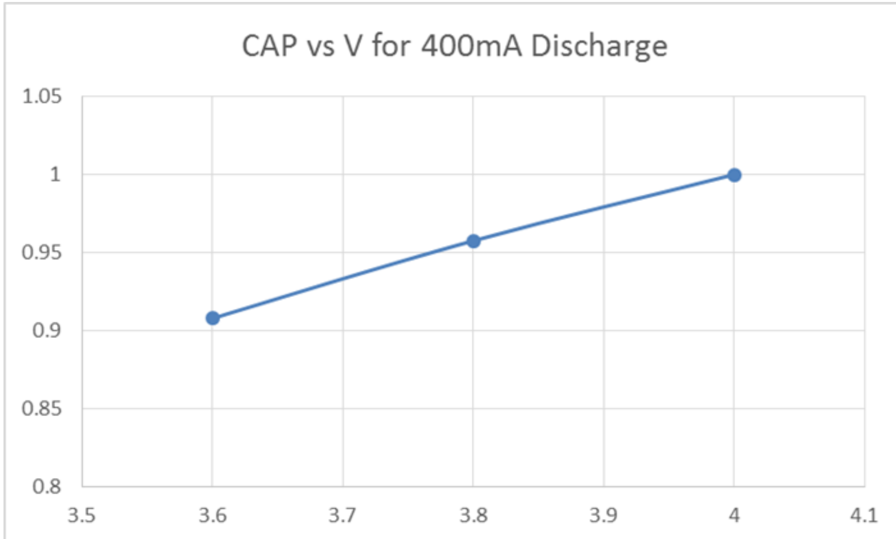

Figure 4. Rated capacity (4 Volt) to capacity as a function of voltage

Equating Initial Capacitance to rated Capacity and State of Health

Initial capacitance readings will be higher than rated capacity. The data of Figure 5 shows that the initial measured capacitance is on the order of 20% greater than rated capacity.

Test Current (A)	0.2	0.4
Old-New ESR %	167.73%	184.91%
Old-New Capacity %	96.83%	95.55%
Old-New Energy %	95.65%	92.59%
Old-New Capacitance @ 3.6V %	97.85%	92.99%
Old-New average Capacitance (%)	97.7%	95.1%
New ratio Capacitance to Capacity at 3.6V (%)	118.0%	120.2%
Old ratio Capacitance to Capacity at 3.6V (%)	119.2%	116.9%
Capacitance to rated Capacity at 3.6V (%)	121.1%	119.9%

Figure 5. Relationship between capacity and initial capacitance for new (product as shipped from the factory) and old (2000 hours held at 3.8V and 65C) cells (same cells were used for new and old)

Further, as the cell ages, this relationship is preserved with the capacitance verses voltage profile shown in Figure 6.

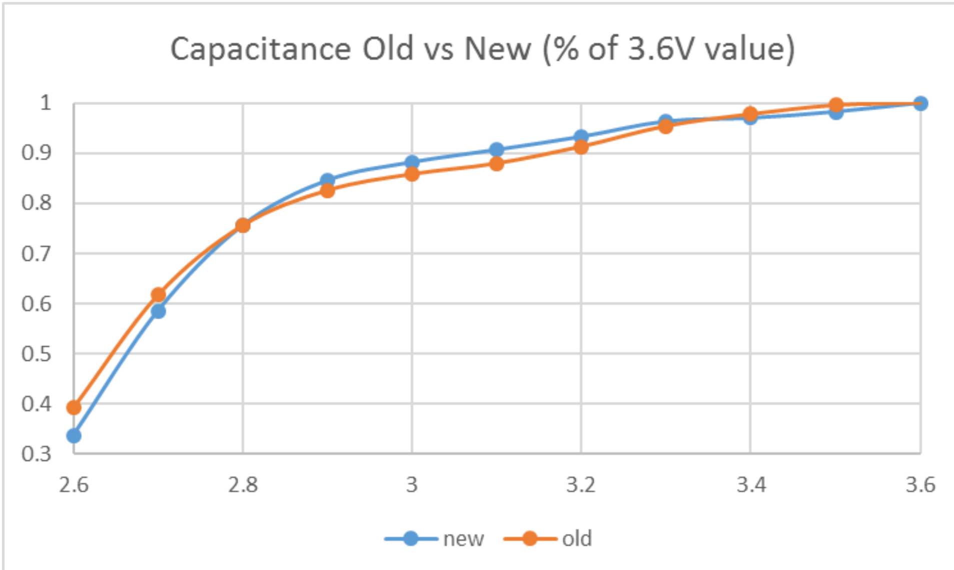

Figure 6. Measured capacitance of new and old cells

State of health (SOH) for the PowerRESPONDER® products is determined through the measurement of parameters EDR (DC-ESR) and initial capacitance. Using these parameters and the relationship of initial capacitance to capacity, the remaining energy can be calculated for constant current loads directly or constant power loads iteratively using EQ6. For example, if the initial measured capacitance is 168F then the relationship between capacitance and capacity given in Figure 5 suggests that the capacity of the device is 140F.