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System Sizing Application Note

Two major applications of ultracapacitors are high pulse power applications and short-term hold-up power. Pulse power applications are characterized by very short, but high current delivery to a load, i.e. during the transmit period in a GSM mobile device. Hold-up applications are characterized by the requirement to deliver load power for a period of seconds to minutes.

Each of these applications emphasizes different performance parameters of the device. High pulse power applications benefit primarily from the low internal resistance (ESR), while in hold-up power applications the ultracapacitors high capacitance (C) is interest. When sizing an ultracapacitor application care needs to be taken to look at both the capacitive component as well as the resistive component.

The capacitive component represents the voltage change due to the change in energy within the ultracapacitor. The resistive component represents the voltage change due to the equivalent series resistance (ESR) of the ultracapacitor. Figure 1 illustrates these two components for a constant current discharge. A charge profile will be similar, but voltages will increase rather than decrease. In this document, all analysis will be based on discharges. For multiple step applications, analyze each charge or discharge step separately.

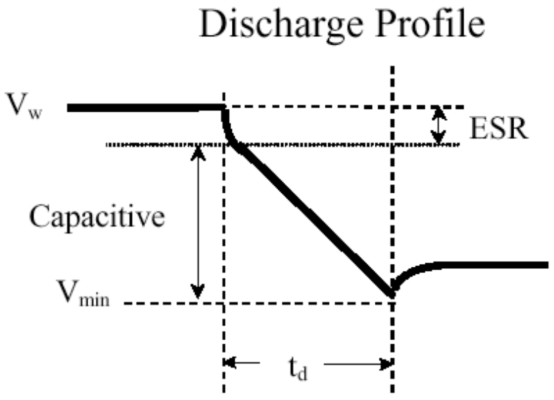

Figure 1: Typical constant current discharge curve

Where

V_w = Normal or working voltage of circuit

ESR = voltage drop due to ESR

Capacitive = voltage drop due to discharge of the capacitor

V_{min} = minimum voltage required to operate the device

t_d = discharge time

As discussed above there are two components to the discharge curve. The resistive part can be calculated by the following equation:

$$Vesr = I * Resr \quad (1)$$

Where

Vesr= voltage drop due to the resistance (volts)

I = constant current supplied by ultracapacitor (amps)

Resr = equivalent series resistance of the part (ohms)

The capacitive part can be calculated by the following equation:

$$dV = I * {}^{dt}/_{C} \quad (2)$$

Where

dV = is the voltage drop due to the capacitance (volts)

I = constant current supplied by the ultracapacitor (amps)

dt = discharge time, t_d in figure 1 (seconds)

C = total capacitance of the part (F)

Therefore by combining equation 1 and 2 one can calculate the total voltage drop of an ultracapacitor during a constant current discharge:

$$dV(total) = I * Resr + I * {}^{dt}/_{C} \quad (3)$$

And the total energy delivered is:

$$J = 0.5\,C\,(Vmax^2 - Vmin^2) \quad (4)$$

Where

dV(total) = is the total voltage drop during the discharge.

I = the current during the discharge of the capacitor. This calculation assumes a constant current during the discharge. Since most applications are approximately constant power, or some other varying current, use the average current for this value. This can be determined by calculating the current at maximum voltage (I_{min} = Power/V_{max}), and at minimum voltage (I_{max} = Power/V_{min}), and averaging the two values.

In some cases, customers indicate a constant current requirement when constant power is required. They often are assuming a constant voltage supply (like a battery or a DC power supply), so they ignore constant power considerations. Verify whether constant current or constant current is required. At lower voltages a constant power requires higher current as the voltage decreases. This is often overlooked during the initial analysis, and can result in under-sizing a solution.

dt = total discharge time for the application

C = ultracapacitor system capacitance. This value will be based on the number of individual capacitors in series or parallel. For ultracapacitors in parallel, the capacitance is additive. For ultracapacitors in series, the capacitance is additive at 1/capacitance. The capacitance will also be affected by the duration of the pulse. Very short pulses will require decreasing the effective capacitance.

$$Ctotal = Ccell * \frac{\#\, of\ cells\ in\ parallel}{\#\, of\ cells\ in\ series} \quad (5)$$

To determine how many cells are required in series, divide the maximum application voltage V_{max} by the maximum allowable cell voltage. The maximum allowable cell voltage is determined by life and temperature considerations. Nominally, this can be assumed to be 2.7 volts per cell.

The number of cells in parallel is determined after the first iteration of this calculation. If the first iteration indicates that there is inadequate capacitance for the application's requirements, the capacitance and resistance can be changed by either putting more cells in parallel or by using larger cells. In some instances, using fewer series cells and choosing to operate the individual cells at higher voltages is an option. This is a trade-off of performance vs. life, since higher operating voltages decrease life. This trade-off must be done on a case-by-case basis.

Resr = the resistance of the complete ultracapacitor system. This value will be based on the number of individual capacitors in series or parallel. The greater the number of cells in parallel, the lower the resistance. The greater number of cells in series, the greater the resistance. Note that this is the opposite of how capacitance is calculated. The resistance will also be affected by the duration of the pulse. Very short pulses will require decreasing the effective resistance.

$$Rtotal = Rcell * \frac{\#\ of\ cells\ in\ series}{\#\ of\ cells\ in\ parallel} \quad (6)$$

Information Needed for Sizing

In order to solve equation 3 there are certain variables that need to be determined. The most common ones are:

Vmax = maximum operating voltage

Vnom = nominal working voltage

Vmin = min voltage the system can function

I = current requirement (or use power to calculate average current)

dt = time of discharge/charge

other parameters to look at are:

needed system life – used to determine the proper cell voltage

operating temperature – used to determine proper cell size and voltage

frequency/duty cycle – used to determine self heating and cooling requirements

If the requirement is for a very low current and the IR drop from the resistive part is small compared to the overall dV the voltage drop due to the ESR affect can be ignored from equation 3. This will simplify the sizing calculation.

Sizing Examples

Below are several examples on different methods of sizing:

Constant Power: Let's assume a transportation system requiring 30 KW of power for 5 sec in order to accelerate a hybrid bus. The system voltage is 300 V and can drop to 150V. One approach is to calculate the total energy needed, 150KJ (30 * 5). Solving equation 4 for C we get:

$$150{,}000 = 0.5 * C * (300^2 - 150^2)$$

C = 4.44 F

Assuming a cell voltage of 2.7V we can determine the number of cells needed in series by dividing the maximum voltage by typical cell voltage and rounding up, thus getting 112 cells. Now assuming no parallel connections we use equation 5 to find the closest cell needed:

$$4.44 = Ccell * \frac{1}{112}$$

Ccell = 497 F

Looking at the cell offering we can pick closest value which is 600F. This method ignores the loss due to the resistive side thus now we can use the data from the 600F cell and the average current required to go back to equation 3 and solve for dV to ensure it is within the limits of the application.

Average current = (P/Vmax + P/Vmin)/2 = (30,000/300 + 30,000/150)/2 = 150A

The ESR for 600F cell is 2.5 mohm, therefore for a112 cell series system the Resr =112 * 0.0025 = 0.28 ohm and Csys=600/112=5.36F. Now solving for dV in equation 3 we get:

dV = 150 * (0.28) + 150 * (5/5.36) = 182V

Since this voltage drop is greater than the application specification limit we will either need to move to the next size up cell or place two series stacks in parallel.

Constant Current: Let's assume a solar application where the ultracapacitors are to provide a backup during the power failure with a current requirement of 0.5 amp. Power needs to be supplied for 7 minutes with a nominal voltage of 24V and minimum voltage of 15V. For this example since the current is very low we can ignore the resistive drop part of equation 3 and simplify it to:

$$dV = I * {}^{dt}/_{C}$$

Solving for C we get:

$C = I * {}^{dt}/_{dV}$ = 0.5 *(7*60/9) = 23 F

The number of cells needed in series is 9 (24/2.7). The cell capacitance needed to achieve 23F at 24V is 207F. Examining the cells data sheets we can select the closest cell which is the 220F cell. To double check we can go back to equation 3 and solve for dV using the data from the 220F cell data sheet to ensure the resistive loss is negligible.

For further assistance please contact Ioxus to discuss your system requirements with one of our application engineers or refer to our sizing worksheet.