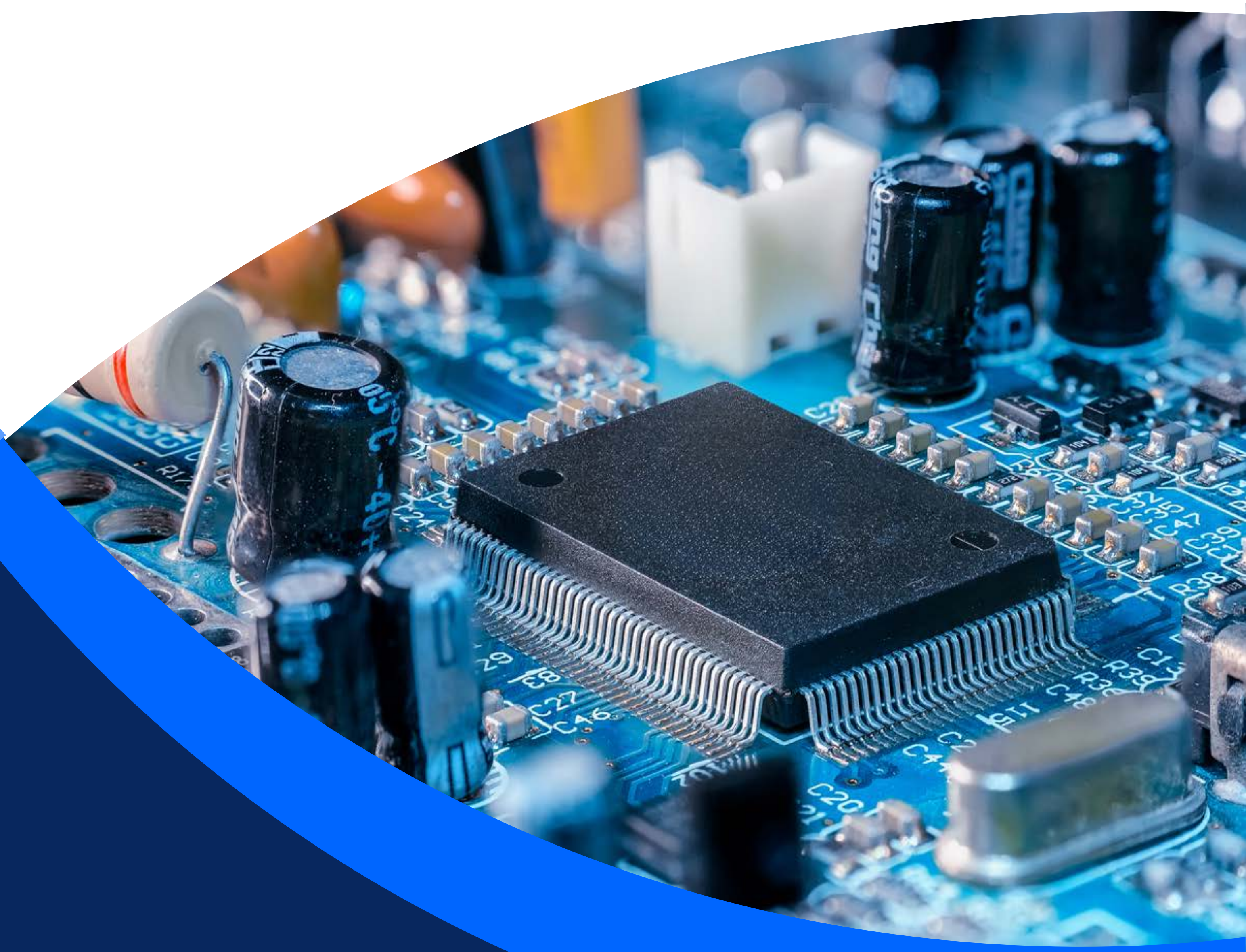

Designing with Supercapacitors

Power Backup

Abracon

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There are many different applications where backup power is needed, and it can vary widely depending on the application. A few examples would be the backup power for an RTC used to transition a laptop from wall power to battery power. In this case, very little energy is needed, and the time required is relatively short, only a few milliseconds. A more extreme example is the power backup of a complete household. The whole home power backup requires kilowatts of power over an extended period of time, from hours to days.

To adequately scope the backup system, the first question that needs to be asked is how long (duration) power backup is needed. Is a long-sustained duration needed to continue powering a whole house or a whole factory floor while the electric service is down? Is the power backup used to notify a user the AC power is lost and to save their work before shutting down, much like a computer power backup system. Knowing the required duration will help determine the type of power source.

The second question to help determine the best power source is how much work needs to be done for the duration of the power loss. Work is mentioned because it allows easy conversion to/from energy and power.

The Ragone plot shown in Fig. 1 illustrates how many different sources of power relate to energy and power capabilities.

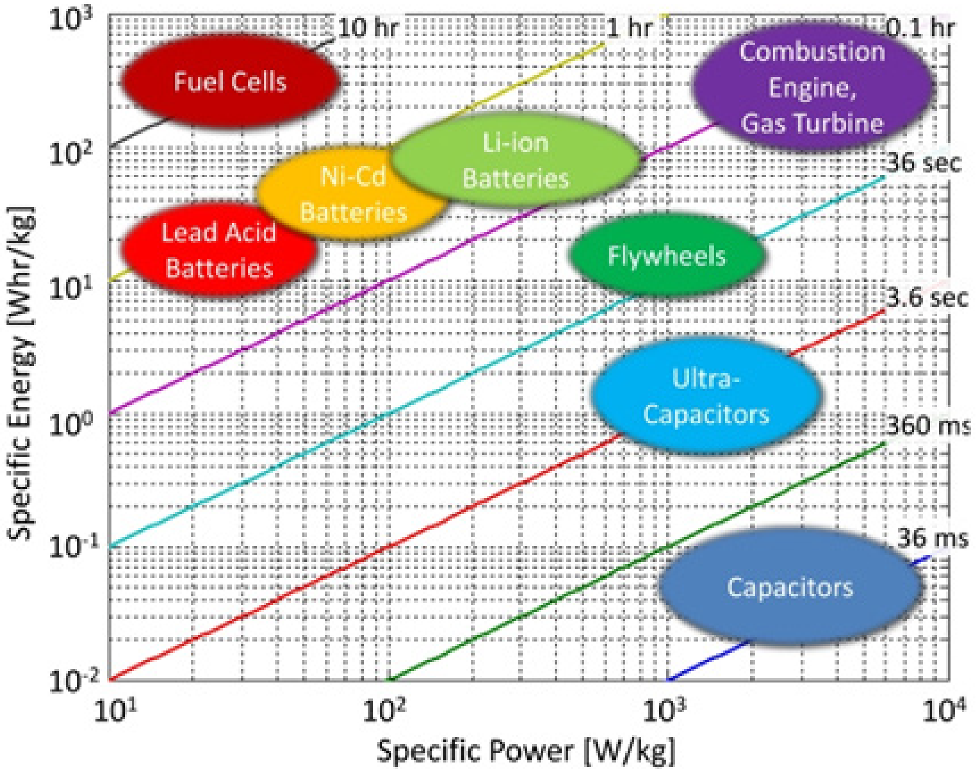


Fig. 1 Ragone plot illustrating the relationship of Power and Energy between several sources (Image: Researchgate)

From Fig. 1, the best overall solution for balancing power output and available energy is the combustible engine. This solution would undoubtedly be best for a high-power, long-duration backup system.

The choice becomes unclear when an application can straddle the use of batteries and supercapacitors. Applications like these require a third question to determine the best overall solution. What is the accessibility and maintainability of the power source?

There is a stark difference between batteries and supercapacitors when it comes to durability and safety. Supercapacitors are far superior in charge/discharge cycles and inherently have no risk of thermal runaway, a characteristic of Li+ batteries that can cause catastrophic fires and explosions of the cells.

Design concept of a Backup Energy Module (BEM)

The concept of a BEM can be anything that can be imagined, but this application note will use the JEDEC standard JESD315, Backup Energy Module Standard for NVDIMM Memory Devices (BEM), 2021, as a reference and focus on the power source.

The JESD specification emphasizes backup power for Storage Array Cards and their associated power requirements. However, this specification could be scaled to any power and energy level needed. In fact, using large supercapacitors supports very high charge and discharge amperages that may be out of the scope of the specification as it is written today.

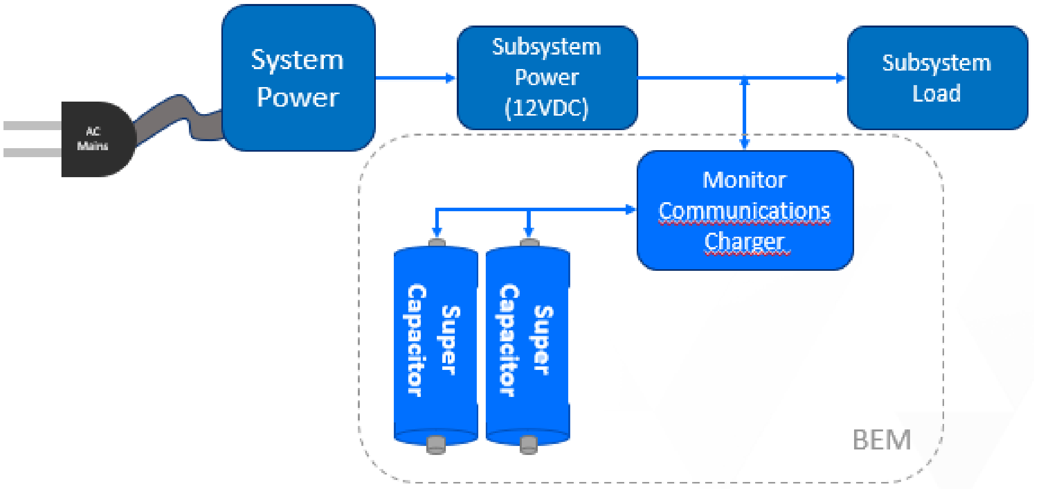


Fig. 2 Conceptual block diagram of a Backup Energy Module using Supercapacitors

Sizing the Supercapacitor

Selecting the correct size of supercapacitor requires characterization of the load that needs backup power. The first questions should be: what is the total work that needs to be completed, and in what timeframe? Supercapacitor parameters that need to be analyzed are the Capacitance, Rated Voltage, Maximum charge/discharge current, Equivalent Series Resistance (ESR), and Rated operating temperature.

For simplicity, consider the load has been characterized as a constant 20 Watts. The JESD315 specification states the BEM needs to support the load for at least 30s. However, in this example, we will use 180s. This means the total amount of work (Energy) in our example is equal to the following:

E = Power * Time, where Power is in Watts and Time is in seconds

If 1 Watt = 1 joule/second, then 20W = 20joules/sec

E = 20joules/s * 180s E

= 3,600 joules

The JESD315 specification states the required minimum energy at initial state of 300joules, therefore our example is well within the specification.

Knowing the amount of work in joules, the capacitance can now be calculated from the total energy (work) and operating voltage of the supercapacitor using the following equation:

Stored Energy: $E = \frac{1}{2}C * V^2$ (joules)

Using a supercapacitor family with an operating voltage of 4.2.V and solving for C

$C = 2 * E/V^2$

$C = 2 * 3600/(4.2)^2$

$C \approx 408$ farads

In an ideal world, a capacitor of at least 408 farads would be sufficient to supply backup power of 20W for 3 minutes. In reality, it needs to be much larger. The reason is that these equations didn't account for real-life restrictions of the power source - discharge current and total capacity.

As with any real-life power source, supercapacitors do not have unlimited discharge current. In the example, the load requires a constant 20W of power. The power is equal to the voltage multiplied by the current. As the capacitor discharges, the voltage drops proportionately. The current must increase proportionately to maintain 20 watts as the voltage decreases. In fact, as the capacitor's voltage approaches zero, the current approaches infinity! There needs to be a limit imposed to circumvent the supercapacitor's self-destruction. The discharge current needs to be limited.

Fig. 3 illustrates a real-life discharge curve based on a supercapacitor almost 10x larger than our previous ideal calculations. As we continue with our example, the reason will become clear.

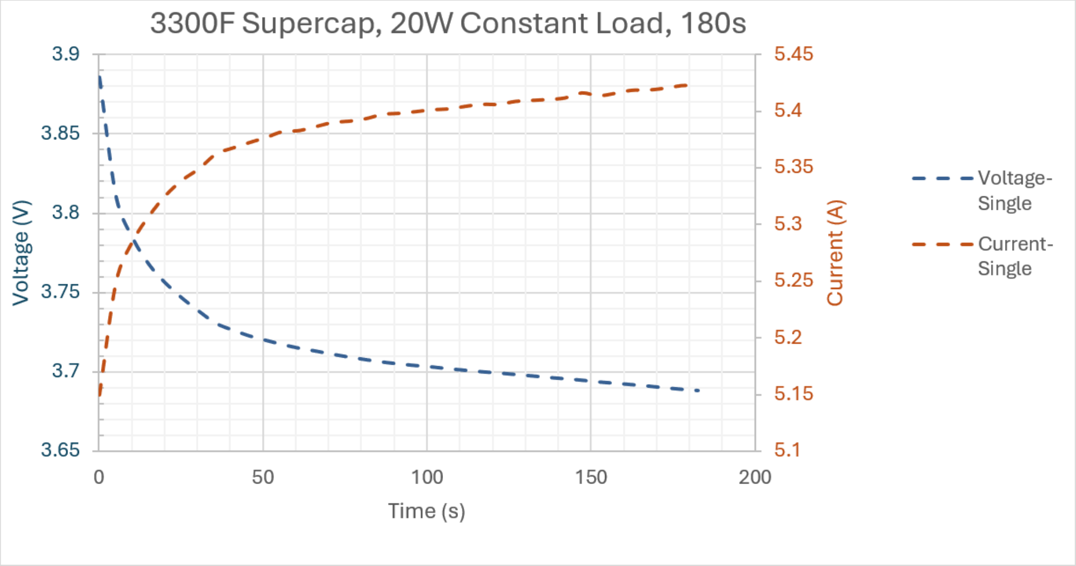


Fig. 3 Graph showing the relationship between Voltage and Current over Time based on a 20W constant load.

The second real-life restriction closely ties into the first - the total usable capacity. In other words, what is the minimum allowed capacitor voltage to achieve 20W of constant power without exceeding the supercapacitor maximum discharge current? The total usable capacity is the amount of charge between the starting and ending voltages, so in reality, using the full capacity of the supercapacitor can never be achieved.

Another way to approach the topic of capacity is to use the supercapacitor's maximum discharge current and work backward to determine the minimum voltage such that the current does not exceed the specification.

Continuing with the example, we'll say the 408F supercapacitor we calculated has a max discharge current of 6A. Using the power equation, the discharge cycle will start at 4.76A (I = 20W/4.2V) and quickly increase to 6A when the capacitor's voltage reaches 3.3V (20W/6A). The time for this discharge can be calculated using the following constant power equation:

$$T_{discharge} = (1/2P) * C * (Vstart^2 - Vmin^2), \text{ where } Vstart=4.2V, Vmin=3.3V$$

$$T_{discharge} \approx 68s, \text{ where our goal was } 180s$$

This calculates to about 1,360 joules of work, where our goal is 3600 joules. Due to the supercapacitor's discharge current limit, the usable capacity is diminished considerably.

Another real-life characteristic affecting the usable capacity of the power source is its internal resistance. Supercapacitors for DC applications refer to this as the ESR, as previously described.

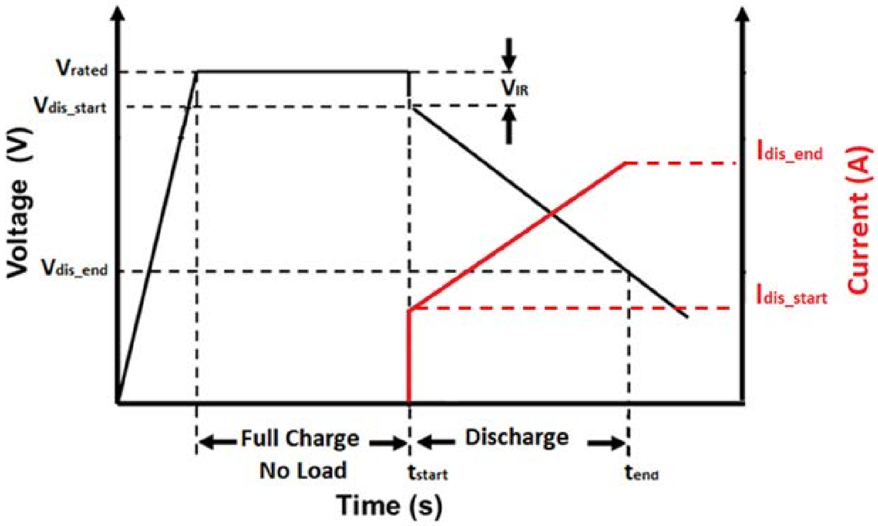


Fig 4. Discharge graph showing the effects of ESR on voltage (V_{IR}).

Fig. 4. Illustrates a voltage drop caused by the supercapacitors ESR referred to as VIR. Therefore, in our example, the starting voltage is not 4.2V. The voltage drop is calculated as Vdrop = ESR * Idischarge. The starting current for the discharge cycle was 4.76A, and with a typical supercapacitor ESRx2 = 0.018Ω*2 = 0.036Ω. This calculates to Vdrop ≈ 0.17V and a starting discharge voltage (Vdis_start) of 4.03V. This means the discharge cycle will provide less joules for a shorter duration.

Accounting for real-life consequences has left the original calculation of 408F an ineffective solution. In fact, this example did not account for the supercapacitor's tolerance or any consideration of the total lifespan of the supercapacitor as it relates to the operating voltage and ambient temperature of the environment.

How to Size a Supercapacitor Without Going in Circles

To some readers, it may be becoming more clear how to accurately size a supercapacitor for a given load. However, just to make sure, this section will put all the puzzle pieces together. The next example will take the previous load requirements and consider the real-life restrictions first. At the end of the analysis, the result will be the recommended capacitance.

In this example, the load remains 20W; therefore, the joule calculation of total energy or work of 3600 joules still applies.

The first consideration is the rated maximum discharge current. Just as before, the minimum allowable discharge voltage was calculated to be 3.3V such that the discharge current does not exceed the 6A specification.

The starting voltage of the discharge cycle, taking the worst-case ESR VIR (0.17V) into consideration, is now 4.03V. The constant power equation can be used to find the capacitance as a function of time (180s) and voltage:

$$\text{Tdischarge} = (1/2P) * C * (\text{Vstart}^2 - \text{Vmin}^2) \quad C =$$

$$(180\text{s} * 2 * 20) / (\text{Vstart}^2 - \text{Vmin}^2)$$

$$C \approx 1340 \text{ Farads}$$

At this point, it is best to factor in the supercapacitor's tolerance. The datasheet specifies the capacitance as 'typical .'Therefore, we need to add capacitance to our calculated value. For the example here, the supercapacitor has a tolerance of ±20%. To compensate for the worst case, the 1,340F capacitance must be increased by 20%, or a total of 1,675F.

As stated previously in the Abracon app note titled Supercapacitors vs. Batteries, batteries and supercapacitors are sensitive to high temperatures, which can significantly reduce the endurance or lifetime of the component. Please refer to the app note titled Supercapacitor Lifetime Explained for more detailed information about derating the operating voltage to extend the life and endurance of the supercapacitor.

Continuing our example, the BEM will reside in a blade server that contains active cooling to maintain the ambient temperature inside the chassis at 60°C maximum. The supercapacitor family chosen for this application has an operating temperature range of -20°C to +60°C. The maximum ambient temperature is right at the supercapacitor's maximum operating temperature. This needs to be analyzed further.

Temperature affects the supercapacitors' endurance or longevity. How long is the BEM expected to operate before being replaced or decommissioned? For our example, 2 years will be used.

As an industry standard, a supercapacitor's lifetime is considered 'expired' when the capacity has decreased by 30%. This means if the supercapacitor is sized correctly at the end of its life at 2 years, 30% less joules will be stored. However, none of the previous calculations contain any design margin except for compensating for the supercapacitor's worst-case tolerance. This will be insufficient for a 2-year lifespan. The easiest way to compensate is to add 30% to 1675F, yielding a supercapacitor of 2,297F.

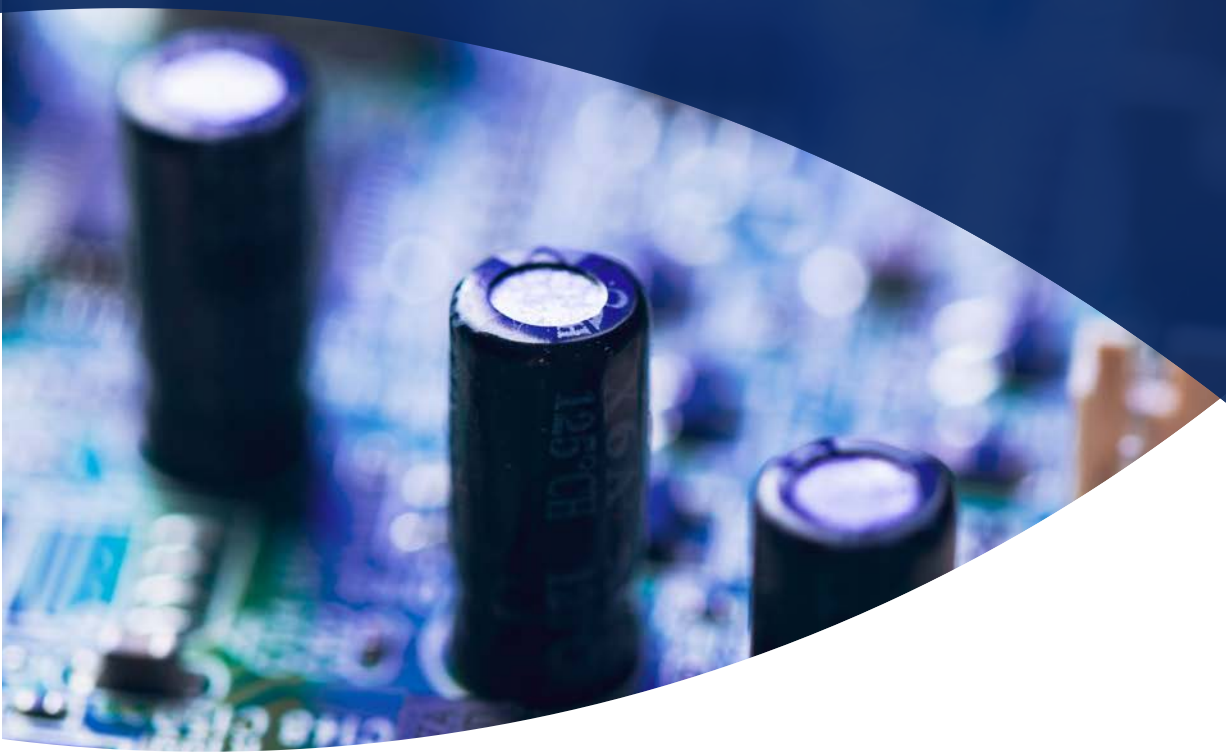
We are not done, though! Another industry standard is to specify the lifetime of a supercapacitor as 1,000 hours operating at its rated temperature and voltage. This is equivalent to a little over 1 month of continuous operation. What?! Don't shoot the messenger.

Given the rated voltage, rated temperature, and 1,000 hours, the lifetime can be extended by derating the voltage and/or the operating temperature. The example here requires an ambient temperature of 60^0C, consequently providing no room to derate the supercapacitor's temperature. The only option is to derate the voltage. In order to achieve 2 years of life, the voltage needs to be derated to ~3.8V. After considering the ESR voltage drop of approximately 0.2V, yields a total discharge cycle between 3.6V and 3.3V. Recalling that 3.3V was the minimum voltage allowed such that the discharge current did not exceed the supercapacitor's current rating specification.

Using this equation again to solve for C,

$$C = (180s * 2 * 20) / (Vstart^2 - Vmin^2)$$

The capacitor needs to be ~3,500 farads to account for voltage derating. The 3,500F value represents the capacitance required at the ‘end’ of its life to still be operational. This capacitance value does not account for the supercapacitor’s tolerance of 20% and lifetime degradation of 30%. After these factors are considered, the total capacitance needs to be ~6250 farads at the beginning of service. For more information about how a supercapacitor’s aging affects usable capacity and ESR, please refer to the application note titled Supercapacitor Lifetime Explained to learn more about derating supercapacitors.



Conclusion

Hopefully, this app note has shed some light on the intricacies of designing a power backup source with supercapacitors. It is best to use the real-world limitations found in the supercapacitor's datasheet and apply them to the equations mentioned previously.

Basic calculations yielded a 408F supercapacitor, but after all the analysis, the best solution for 20W of continuous for 180s, lasting 2 years in the field, requires a 6250F supercapacitor, 15X larger in capacity.

This begs the question, how much physically larger is the 6250F supercapacitor than the 408F? The 408F would need to be rounded up to the next higher standard capacity of 470F. As an estimate only, the 470F supercapacitor dimensions would be approximately Ø16mm x 34mm, while the 6250F dimension would be approximately Ø24mm x 70mm. Both are cylindrical, which means there is a ~5X difference volumetrically.

Below is a recommended process for accurately sizing a supercapacitor. The order of steps may differ depending on the application.

1. Accurately characterize the load. This first step is critical for all subsequent steps. Calculate the amount of work or stored energy that is required. Add design margin to compensate forc efficiencies that would affect the calculation, e.g. DC/DC efficiency. Keep in mind that DC/DC efficiency is not constant and may decrease as the input voltage to the boost circuit decreases (supercapacitor voltage).

2. Calculate the minimum capacitor voltage allowed without exceeding the rated current. Use worst-case power to compensate for load variations and/or add design margin by backing off the supercapacitor's rated current by some percentage.

3. Derate the charge voltage and/or ambient temperature to achieve the desired life expectancy.

4. Determine the starting voltage after calculating the ESR voltage drop, such that (Vstart = Vderated – Vesr). The ESR used in this calculation should be 2-3x of the datasheet value to compensate for the aging effects on supercapacitors.

5. Calculate the capacitance required for the time duration of the backup using $C = (t * 2 * P) / (Vstart^2 - Vmin^2)$, where t is in seconds and P is in watts.

6. Add a percentage of capacitance to accommodate for worst case tolerance.

7. Add capacitance to accommodate for degradation of supercapacitor over lifetime, typically 30%.

8. Finally, to check our calculations and determine if enough energy is provided, the capacitance at the end of life is used (3500F).

Energy Consumed = Stored Energy before discharge – Stored Energy after discharge
Stored energy before discharge = ½ * C * Vstart^2 = ½*3500*$(3.6\text{V})^2$ = 22,680 joules
Stored energy after discharge = ½ * C * Vmin^2 = ½*3500*$(3.3\text{V})^2$ = 19,058 joules
Energy Consumed ≈ 3623 joules
The original requirement was 3600 joules, so this will work!

Fig. 5 shows a summary of all the calculated parameters and is illustrated on the discharge graph included below:

5500F Super Cap:
  Vrated = 4.2V
  Imax = 6A
  ESR = 0.025Ω
  Lifetime = 2 years
Load:
20W constant Power load

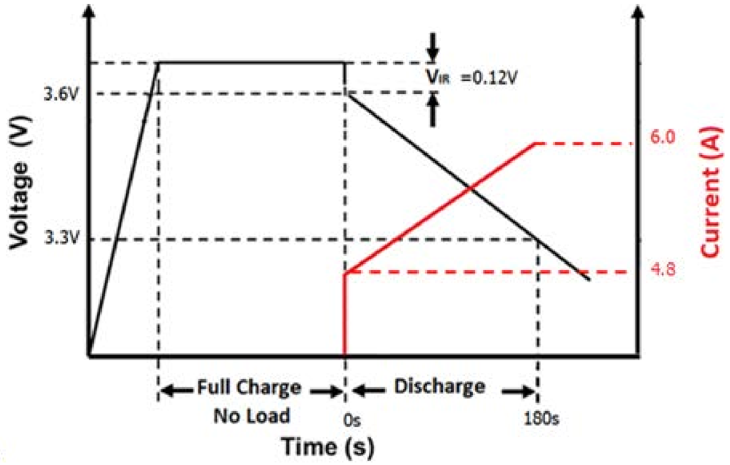


Fig. 5 Discharge chart with calculated values based on the app note example.