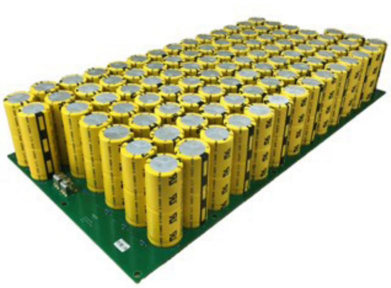
# Supercapacitor modules application guidelines



## Overview

Supercapacitor modules are an emerging technology in larger scale energy storage segment for infrastructure backup power, peak power shaving, heavy transportation, automotive, utility grid and microgrid services. This document provides basic guidelines for applications using electric double-layer capacitors (EDLC), also known as supercapacitors or ultracapacitors. While there are many guidelines that are common with more traditional printed circuit board level supercapacitors, there are certain characteristics that are unique to higher voltage modules. Eaton defines a supercapacitor module as a distinct number of supercapacitor cells that are assembled in series or parallel within a single suite resulting in higher voltage or increased capacitance. If questions arise during your development process and are not answered in this document, please contact technical support or your local Eaton sales representative (click here).

## Lifetime

Eaton supercapacitor modules have a longer lifetime than most battery chemistries, but their lifetime is not infinite. The basic end-of-life failure mode for a supercapacitor is an increase in equivalent series resistance (ESR) and/or a decrease in capacitance. The actual end-of-life criteria are dependent on the application requirements. Prolonged exposure to elevated temperatures, high applied voltage and excessive current will lead to increased ESR and decreased capacitance. Reducing these parameters will lengthen the lifetime of a supercapacitor. In general, supercapacitors used in modules have a similar construction to electrolytic capacitors, having a liquid electrolyte inside an aluminum can sealed with a rubber bung. Over many years and charge/discharge cycles, the supercapacitor cells contained within the module will dry out, causing high ESR and eventually end-of-life. Performance characteristics and resulting changes in ESR and capacitance are listed on individual module data sheets.

## Voltage

Supercapacitor modules are rated with a nominal recommended working or applied voltage. The values provided are set for long life at their maximum rated temperature. If the applied voltage exceeds this recommended voltage, the result will be reduced lifetime. If the voltage is excessive for a prolonged period, gas generation will occur inside the supercapacitor cells and may result in leakage within the module. Short-term overvoltage can usually be tolerated by the supercapacitor module, but not recommended.

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## Discharge characteristics

Supercapacitor modules are intended as energy storage with a sloping DC voltage curve in either constant current or constant power. Example constant power and constant current discharge curves can be seen in Figure 1a and Figure 1b respectively. When determining required capacitance, and resulting ESR, for an application, it is important to consider both the resistive and capacitive discharge components. In high current, rapid pulse applications, the resistive component from module ESR is the most critical. In low current, longer duration applications, the capacitive discharge component is the most critical. The formula for the voltage drop, Vdrop, during a discharge at I current for t seconds is:

Vdrop = I(R + t/C)

To minimize voltage drop in a rapid pulse application, use a supercapacitor module with lower ESR (R value). To minimize voltage drop in a low current application, use a supercapacitor with large capacitance (C value). Please refer to the data sheets (click here) for supercapacitor module specifications to assist in matching these characteristics to application requirements.

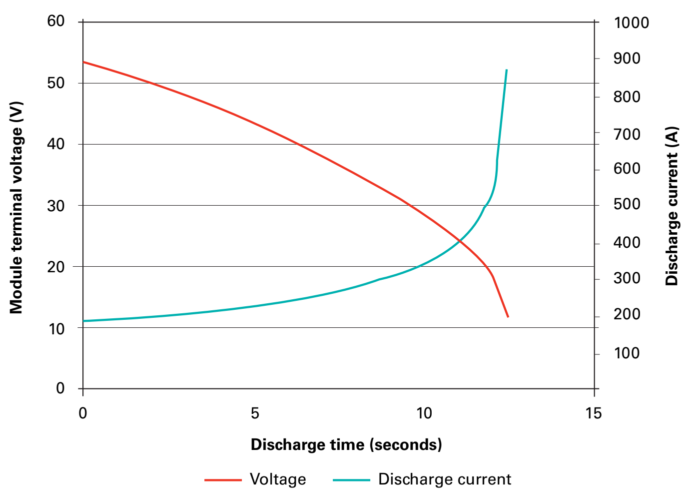


**Figure 1a.** Example voltage and current discharge curves for 10 kW discharge from one module with 56 V float voltage.

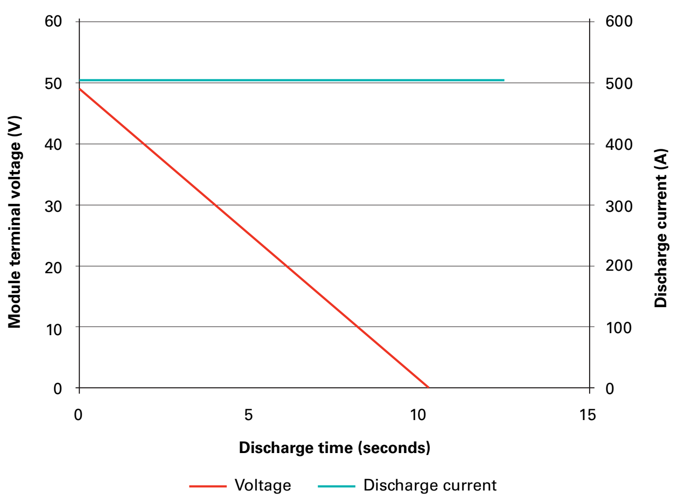


**Figure 1b.** Example voltage and current discharge curves for 500 A discharge from one module with 56 V float voltage.

## Charging

Supercapacitor modules can be charged using various methods including constant current, constant power, constant voltage or by paralleling to an energy source, i.e. battery, fuel cell, DC-DC converter, etc. Many battery chargers and equalizers, DC-DC converters and bi-directional inverters are often used to charges supercapacitors, however due to the low ESR of supercapacitors, a maximum charging current should be ensured to not mimic a short circuit condition. Typically, this is done through firmware modifications in the charging logic or through added resistance in the charging circuit.

If a supercapacitor module is configured in directly parallel with a battery where the battery is intended to charge the supercapacitors, adding low value impedance in series between the battery and supercapacitor will reduce the charge current to the supercapacitor module from the battery and will also increase the life of the battery. If series impedance or resistor is used, ensure that the voltage outputs of the supercapacitor are connected directly to the load and not through the resistor, otherwise the low impedance of the supercapacitor will be nullified. Also, battery systems exhibit decreased lifetime when exposed to high current discharge pulses. Often in supercapacitor and battery hybrid energy storage systems, power electronics are integrated that can provide a control strategy to charge/discharge the appropriate energy storage based on the power requirements. The power electronics may also be programed to optimize the charging power flow between energy storage technologies.

Supercapacitors are generally less restrictive in the rate at which they can be charged when compared to other energy storage technologies. One of the key considerations to help determine the appropriate charging rates is the resulting temperature rise. This temperature rise is represented by the following equation:

$\text{Delta T} = I_{RMS}{}^2 * R_{ESR} * R_{th}$

The thermal resistance, $R_{th}$, of supercapacitor modules have been experimentally determined assuming free convection. Module thermal resistance and $R_{ESR}$ is provided on respective data sheets; however the $R_{ESR}$ should be converted to Ω when applying the equation above. Using the $R_{th}$ value, a module temperature rise can be determined based upon RMS current. The $I_{RMS}$ should account for the charging and discharging current and factor in the non-cycling periods over a given timeframe.This results in higher duty cycle applications having a higher $I_{RMS}$. The effects of this temperature rise plus the ambient temperature is described in the next section. Since supercapacitors have very low $R_{ESR}$, often measured in mΩ, ambient temperature is often the most prevalent temperature factor.

## Ambient temperature

The standard operating temperature range for Eaton supercapacitor modules is –40 °C to +65 °C. Temperature in combination with voltage can affect the lifetime of a supercapacitor. In general, an increase of ambient temperature by 10 °C will decrease the lifetime of a supercapacitor by a factor of two. As a result, it is recommended to use the supercapacitor at the lowest temperature possible to decrease internal degradation and ESR increase over time. If this is not possible, decreasing the applied voltage to the supercapacitor will assist in offsetting the negative effect of the high temperature. For instance, +85 °C ambient temperature can be reached if the applied voltage is reduced by ~30 percent per supercapacitor.

At temperatures lower than normal room temperature, it is possible to apply voltages slightly higher than the recommended working voltage without significant increase in degradation and reduction in lifetime. Raising the applied voltage at low temperatures can be useful to offset the increased ESR seen at low temperatures. Increased ESR at higher temperatures is a result of permanent degradation / electrolyte decomposition inside the supercapacitor cells. At low temperatures, however, increased ESR is only a temporary phenomenon due to the increased viscosity of the electrolyte and slower movement of ions.

Figure 2 plot shows the effect on lifetimes by reducing continuous operating voltages for the XLM-62 module. This can be used to estimate the operating life for specific applications where the minimum allowable operating voltage per module is known.

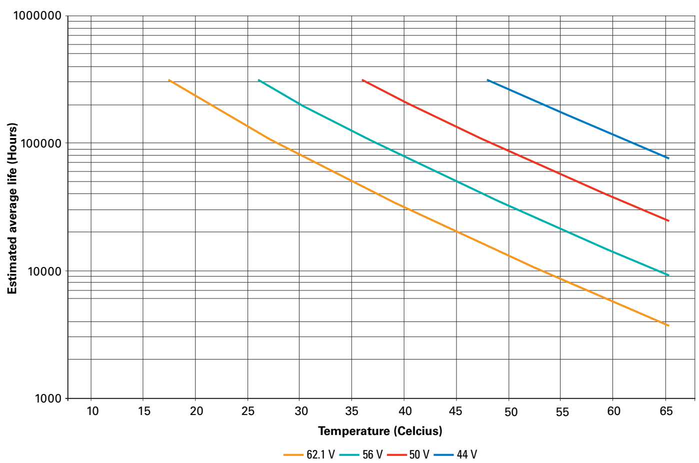


**Figure 2.** XLM-62 life plot at 62.1 V, 56 V, 50 V, and 44 V.

As Figure 2 illustrates, cooler module operation equates to longer service life, all other factors remaining equal. In most applications, natural air convection should provide adequate cooling. In very high duty cycle or high ambient temperature applications, forced airflow may be required to maintain long lifetimes that are inherent to supercapacitors.

## Series and parallel configurations

Individual supercapacitor modules have voltage ratings described earlier. As many applications require higher voltages, supercapacitor modules can be configured in series to increase the working voltage, which is referred to a module string. Similarly, supercapacitor modules parallel to meet application needs with respect to current or power required over a desired timeframe. To assist in determining the number of modules in series and those subsequent strings in parallel, Eaton has developed a calculator tool (click here) containing all supercapacitors. This calculator provides high level high level electrical characteristics (at data sheet end-of-life conditions) and matching these characteristics to various supercapacitor configurations / alternatives. The requested information will require the following information:

- Discharge type (constant power or constant current)
- Power or current required (based on above selection)
- Discharge time
- Maximum system voltage
- Operating voltage
- Minimum system voltage

For information specific to modules within the supercapacitor calculator, please select the tab "Modules" after entering and confirming the initial requirements as depicted in Figure 3.

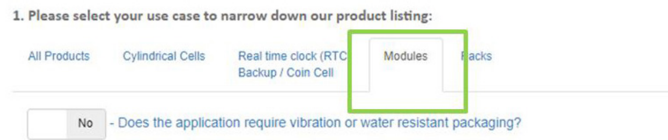


**Figure 3.** Supercapacitor calculator tool screenshot.

Figure 4 is an example output from the supercapacitor calculator that illustrates the discharge curve in a constant power application using the XLM-62R1137A-R with the Figure 5 user inputs.

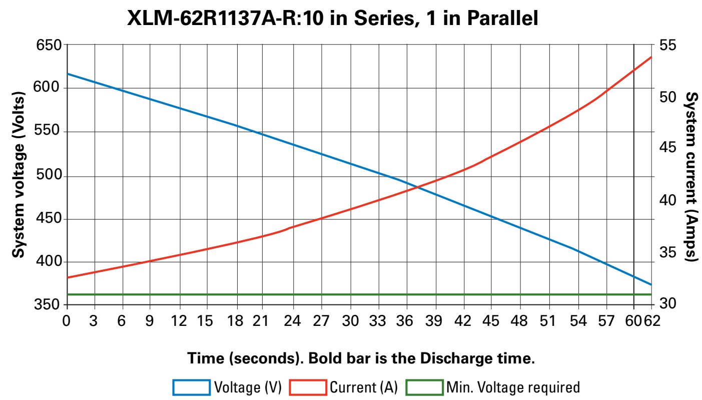


**Figure 4.** XLM-62R1137A-R calculator output using Figure 5 inputs.

User Inputs:

| Power (W) | Discharge Time (s) | System Max. Voltage (V) | Operating Voltage (V) | System Min Voltage (V) |
|---|---|---|---|---|
| 20000 | 60 | 620 | 620 | 360 |

**Figure 5.** Calculator user inputs example.

There is an upper limit to the number of modules that can be placed in series due to the voltage creepage and clearance within the auxiliary circuitry along with the dielectric strength of the enclosures. Each provides their own voltage limit. Please consult the module data sheet and instruction manual for specifics on each module. This string voltage limit is measured to ground, so a floating ground or ungrounded system can offer the ability to extend the working voltage of the system while the individual positive and negative strings remain below the maximum string voltage. Please consult local electrical codes and standards for additional requirements of this topology. Each of Eaton's modules is capable of being assembled in series to achieve voltage ratings higher than 600 Vdc to support the vast majority of low voltage electrical power distribution systems.

Voltage imbalance between modules can occur during all operation states if there are large differences in capacitance value, so it is recommended that strings of individual modules contain the same module family of similar capacitance. A string of modules does not need to be fully replaced if one module has reached end of life or is discovered to be faulty. However, the new module's capacitance value should be within 20 percent of the modules within the string. It is important to ensure that the individual voltages of any single module do not exceed its maximum recommended working voltage as this could result in reaching end-of-life before intended.

## Installation considerations

Attachment to the output terminals can be made through ring lugs or bus bars of the appropriate size for the application. A study should be performed to evaluate the current during cycling through the entire cycle and sized to accommodate the maximum current throughout the entire supercapacitor module string. High power density, fast response and low ESR is a key feature of supercapacitors thus selecting termination methods and wire sizes and/or bus bars to maintain the benefits of low string resistance. Wire sizing should be evaluated to the applicable end-product standards and the governing installation codes and directives.

Supercapacitors, due to their very low ESR, can provide dangerous fault currents if short circuited while fully charged. This danger is increased if a series of modules is assembled together, elevating the operating voltages. For installations, an arc flash study is recommended and action taken if hazards are observed to be potentially present. External overcurrent protection is recommended to be evaluated to ensure personal safety for unplanned events by limiting fault currents. With high voltage and high potential fault currents, current limiting overcurrent protection are recommended for these applications. Eaton offers a suite of trusted overcurrent protection solutions with Bussmann series high speed fuses and Direct Current Molded Case Circuit Breakers to address high fault current applications.

## Self-discharge and leakage current

Self-discharge and leakage current are essentially the same thing measured in different ways. Due to supercapacitor construction there is a high impedance internal current path from the anode to the cathode. This means that to maintain the charge on the capacitor, a small amount of additional current is required. During charging this is referred to as leakage current. When the charge voltage is removed, and the capacitor is not loaded, this additional current will discharge the supercapacitor and is referred to as the self-discharge current. To get a realistic measurement of leakage or self-discharge current, the supercapacitor module must be charged for more than 100 hours; this again is due to the supercapacitor construction. The supercapacitor module can be modeled as several capacitors connected in parallel each with an increasing value of series resistance. The capacitors with low values of series resistance charge quickly thus increasing the terminal voltage to the same level as the charge voltage. However, if the charge voltage is removed, these capacitors will discharge into the parallel capacitors with higher series resistance if they are not fully charged. The result of this being that the terminal voltage will fall giving the impression of high self-discharge current. It should be noted that the higher the capacitance value, the longer it will take for the device to be fully charged. See Methods for measuring capacitance,inflow current, internal resistance and ESR application note (click here) for more details.

## Module management system and cell balancing

As described in the Overview, supercapacitor modules are defined as a distinct set of supercapacitor cells assembled in series and/or parallel in a single physical package. To achieve the long lifetimes that are inherent of supercapacitor cells at a module level, the cells within the module need to be voltage balanced during charging, while charged and during discharging. There are different methodologies of performing this activity with different resultng characteristics. The three most common are passive balancing, shunt balancing and active balancing. Each of these is briefly described below:

- **Passive**: uses voltage dividing resistors in parallel with each supercapacitor cell assembled in series to naturally allow current to flow from high voltage cells to low voltage cells.
- **Active:** monitors and manages each cell voltage to be balanced equally if adjacent cells become out of balance.
- **Shunt:** Uses voltage sensing shunts that activate to maintain each cell voltage under a specified voltage limit.

Eaton's supercapacitor modules each contain preinstalled balancng circuits to ensure proper and safe operation. These balancing schemes do not require external controls or monitoring which can help provide integration simplicity. Each of these three methods can provide an advantage in how the modules are used. For applications that can manage slightly higher self-discharge, passive balancing is likely the most cost-effective option. For applications requiring lower self-discharge, shunt balancing is recommended. Active balancing should only be desired for applications that only need one individual module due to the nature of its balancing scheme. Applications that will require series and/or parallel module strings should have passive or shunt balancing.

Additional information can be deduced from the nature of the charge and discharge characteristics of supercapacitor modules that can be monitored externally through power electronics or other control schemes. Given the predictable nature of supercapacitor discharging, if able to monitor and measure voltage from the module, the state of charge (SOC) can be inferred by the relationship between voltage and remaining energy, specifically useable energy. If setting the maximum voltage as 100 percent SOC, then minimum application voltage (in constant power applications, the maximum current could be the limiting factor), can be set to 0 percent. Then use a linear relationship between voltage and state of charge to infer approximate state of charge.

## Maintenance

Any maintenance or installation should only be performed by properly trained personnel and on discharged modules. Measure and confirm module voltage with an appropriate voltmeter. If above 1 V, a resistor pack or load bank can be connected to discharge the stored energy as heat. The discharge system should be properly sized to manage the heat and properly cooled to manage the heat dissipation. Once down to 1 V or less, place an 18 AWG (~1 mm diameter) wire or larger across the module terminals to short the module.

Basic electrical maintenance should be performed just as normal practices for standard electrical distribution equipment. Annual verification of terminal torque, auxiliary connections, suitable cleanliness and confirmation the module is free from damage should be performed to ensure proper long-term operation. No other maintenance is required.

## Ripple current

Although Eaton's supercapacitors have very low resistance in comparison to other supercapacitors, they do have higher resistance than aluminum electrolytic capacitors and are more susceptible to internal heat generation when exposed to ripple current. In order to ensure long lifetime, the maximum ripple current recommended should not increase the surface temperature of the module by more than 3 °C.

## Storage and shelf conditions

The storage and shelf conditions of supercapacitor modules are similar to most other standard low voltage electrical distribution equipment. Extreme temperatures, moisture, corrosive environments and >85 percent relative humidity should be avoided. Modules should always be stored fully discharged and then shorted with a wire across the terminals.

## Shipping and transportation regulations

Since Eaton's supercapacitors are not inherently hazardous components, they are not governed by many of the common hazardous material transportation regulations. However, there is a United Nations regulation number specific to transporting supercapacitors: UN 3499 CAPACITOR. This regulation outlines requirements for product labeling and packaging of electric double layer capacitors. Part of this regulation requires all supercapacitors to be fully discharged and for modules to be shorted with a conductive wire.

All supercapacitors manufactured by Eaton meet the UN3499 regulation when transported as individual cells or transported as modules made by Eaton. When transporting equipment containing supercapacitor modules, the equipment must be packaged in a strong outer packaging with installed modules protected against accidental activation. As with individual supercapacitor cells and modules, any supercapacitor modules within equipment must also shipped discharged and with a shorting wire across the terminals.

## Product standards and regulatory information

Supercapacitors are often designed to and recognized by product standard UL810A: Standard for Electrochemical Capacitors. This product standard governs design and testing of electrochemical capacitors (more commonly called electro-double layer capacitors, supercapacitors and ultracapacitors) for use various power equipment. The standard is inclusive of individual supercapacitor cells or multiple series and/or parallel connected cells with or without associated circuitry. Eaton's supercapacitor and supercapacitor module UL certifications are contained in UL file MH46887.

Eaton supercapacitors are rated non-hazardous under the OSHA hazard communication standard (29 CFR 1910.1200).

## General safety considerations

If a module has been found to be drastically overheating unexpectedly, remove power or load from the module. Allow to cool down and contact Eaton (click here). If asked to dispose, please see disposal procedures below. By nature, supercapacitor modules are energy storage devices that can deliver very high instantaneous power in both high current levels and at high voltages. Only trained personnel in electrical systems and licensed electricians should work on such systems. Modules should be discharged and voltage should be verified before conducting work.

Modules should not be crushed or punctured and should not be stored or operated above +150 °C.

## Disposal procedures

Eaton supercapacitors are non-regulated under RCRA Waste Code. Supercapacitors may however be disposed of by a specialized industrial waste processor or by incineration. Use caution when incinerating as the supercapacitor cells can explode unless it is crushed or punctured prior to incineration. Use high temperature to incinerate the supercapacitor modules as the cell sleeves can produce chlorine gas at lower incineration temperatures.

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