APPLICATION NOTE

Maxwell Technologies®

BOOSTCAP® Energy Storage Modules

Life Duration Estimation

1. Goal

The objective of this document is to explain the way to use the different physical measurements of an ultracapacitor module in order to extrapolate the vital parameters and to estimate the potential operating lifetime of the system.

NOTE: Lifetime performance of ultracapacitors is heavily dependent upon the conditions under which the cells or the modules are being used. The lifetime is affected by operating temperature, operating voltage and other factors such as duty cycle and power flow profiles. The following description is intended to provide a guideline only that can be used to approximate performance life and give a general idea of the expected lifetime under accumulated historical operating conditions. If the conditions of operation change over time into the future, the accuracy of this estimation will be reduced.

2. State of the art

Maxwell Technologies's ultracapacitor modules are well suitable for many heavy transportation, power quality and industrial power back up applications. Once mounted on the vehicle or system, the monitoring of the voltage and the temperature permits the user to adjust the system functions (current, voltage, cooling) to optimize the system function, and finally to prolong their lifetime.

Lifetime prediction is an important piece of information to know for the user. This parameter permits the optimization of the vehicle utilization, and simplifies the logistic if module changes are required.

The available data out of the module from today is limited and does not give any concrete information that can be used to execute a lifetime prediction. At this time, this algorithm has to be integrated by the customer in the application controller.

The procedures and information given in this document are based on the present knowledge of the supercapacitors BOOSTCAP® and is intended to be used by the customer only as a general guideline to predicting how much life may be left in a particular ultracapacitor system.

3. Lifetime definition

The lifetime is defined by the time duration of the module from its first use in the application, until one of the end of life criteria is reached. The two parameters which are necessary to check the end of life criteria are:

- Capacitance;
- ESR (equivalent serial resistance).

The Maxwell defined criteria are:

- A reduction of the capacitance of 20%;
- An increase of the ESR of 100%.

The customer is free to establish their own limits of these two operating parameters as end of life criteria.

It is typical that before the ESR will rise 100% that capacitance does decay to the -20% level. Therefore, capacitance is generally the first parameter to experience end of life based on this arbitrary criteria.

4. Lifetime estimation

During the development of the solution, Maxwell can perform a theoretical estimate of the lifetime of the supercapacitor system with inputs from the customer of the operating conditions expected. This estimation is based on the power and temperature profile provided by the customer for the application. The power profile permits the calculation of the voltage distribution during a cycle and the theoretical heating of the cells is calculated with the corresponding current levels. Voltage distribution, ambient temperature and heating are the necessary parameters for Maxwell to estimate the lifetime. The design of the system can then be optimized in order to reach the customer requirements.

5. Estimated Life Duration (ELD)

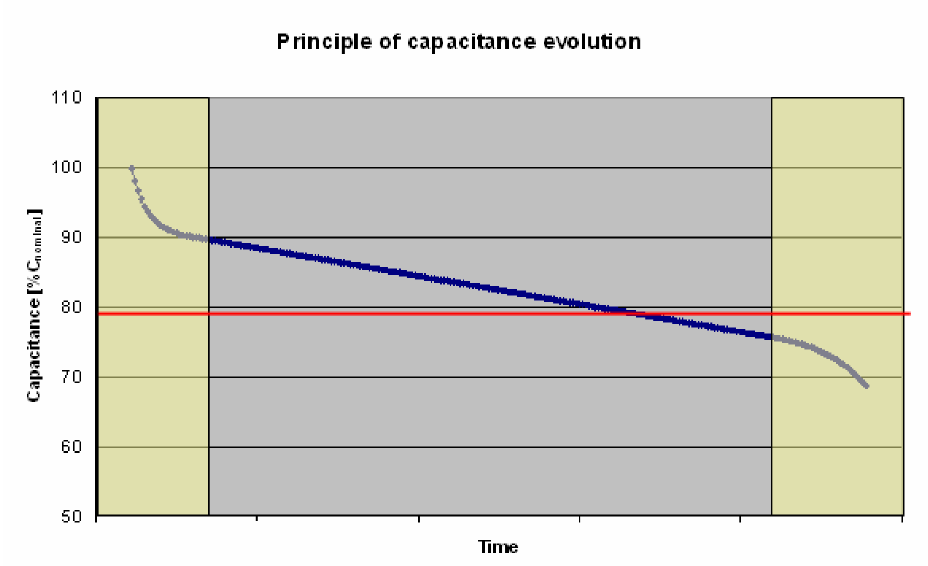
The Estimated Life Duration corresponds to the time between the measurement and the 80% decrease of capacitance, or the remaining life of the module at the moment when the measurements and calculations are done. The ELD calculation does not take into account the MTBF of the module but is rather based only on the evolution of the capacitance with time. In this model it is based on historical information and uses profiles which are extrapolated backward from the condition of the module at two different times. The longer the period between the two times, the more representative of the real performance of the module the data will be.

5.1. Capacitance evolution

The evolution of the capacitance is separated in 3 domains:

1. Exponential decrease during the first hours/cycles
2. Linear decrease during the main part of the life
3. Slow exponential decrease due to natural aging of the supercapacitors

This model applies only when the module is operating in domain 2 in which there is linear decrease of capacitance over time. To apply this model to one of the other domains is running the risk of inaccuracy due to the transient nature of these conditions.



5.2. ELD calculation

The following procedure should be implemented to determine the estimated lifetime duration:

a) Measure of the nominal capacitance under defined condition: $C_{Nominal}$*
**Note: The $C_{Nominal}$ can be different from the one specified in the datasheet. Depending of the measurement condition, it can be lower. Due to the tolerance of the module it may also be higher. In this case, use the capacitance which is specified in the datasheet as the nominal one.*

b) Calculate the end of life criteria value: $C_{Limit} = 80\% \, C_{Nominal}$ (using 80% of $C_{nominal}$ or whatever percentage you wish to use)

c) Measure the capacitance under defined condition: C_1

d) Wait a predefined period: Δt**

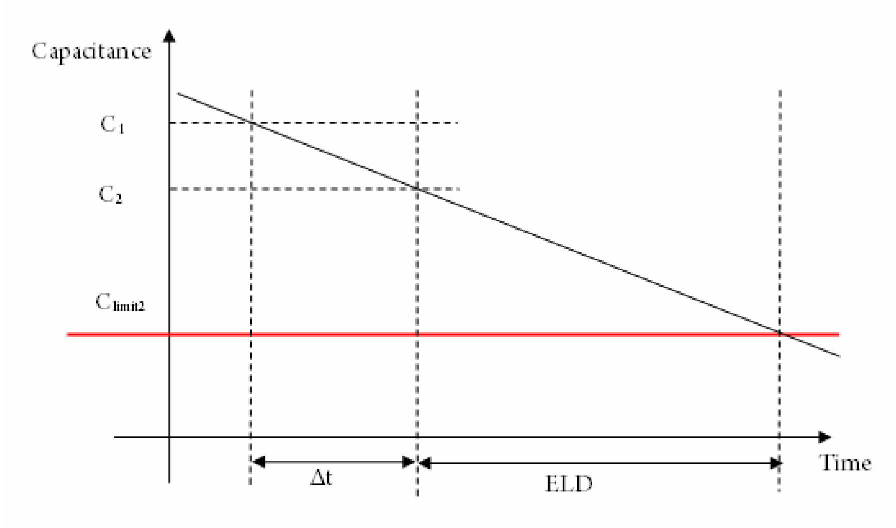
e) Measure the capacitance under the same defined condition: C_2

f) Calculate the estimated life duration (ELD) based on C_{Limit}, C_1, Δt and C_2

$$\frac{C_1 - C_2}{\Delta t} = \frac{C_2 - C_{Limit}}{ELD} \qquad ELD = \frac{\Delta t \cdot (C_2 - C_{Limit})}{C_1 - C_2}$$

g) Wait a predefined period: Δt**

h) Start again at point c)
***Note: this period is application dependant and should be defined together with Maxwell. It will depend upon operating condition stability, the domain in which the module is operating and other criteria*



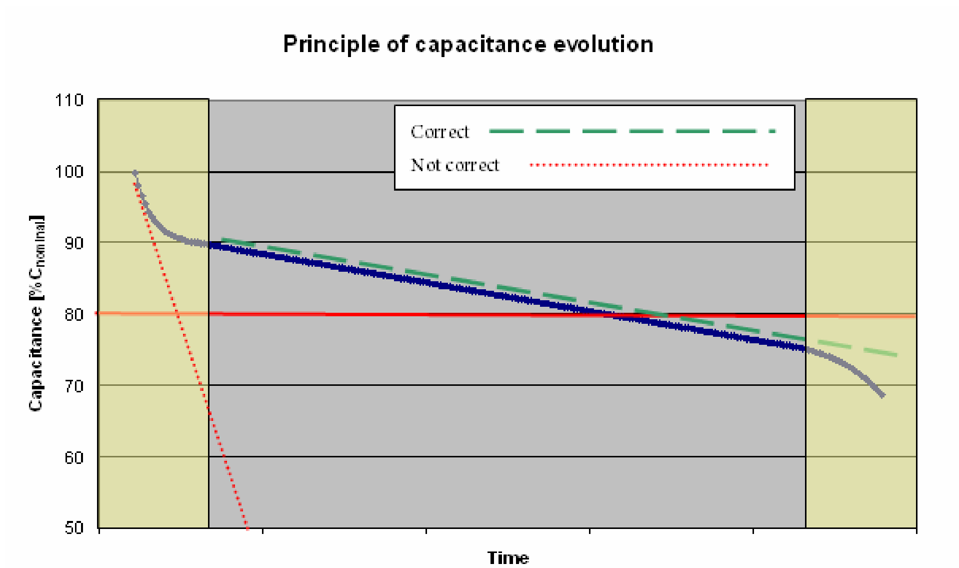
5.3. ELD results interpretation

Two aspects must be checked before trusting the ELD value:

1. Constancy of the ELD value
2. Level of capacitance

The two main reasons for these checks to be done are the following:

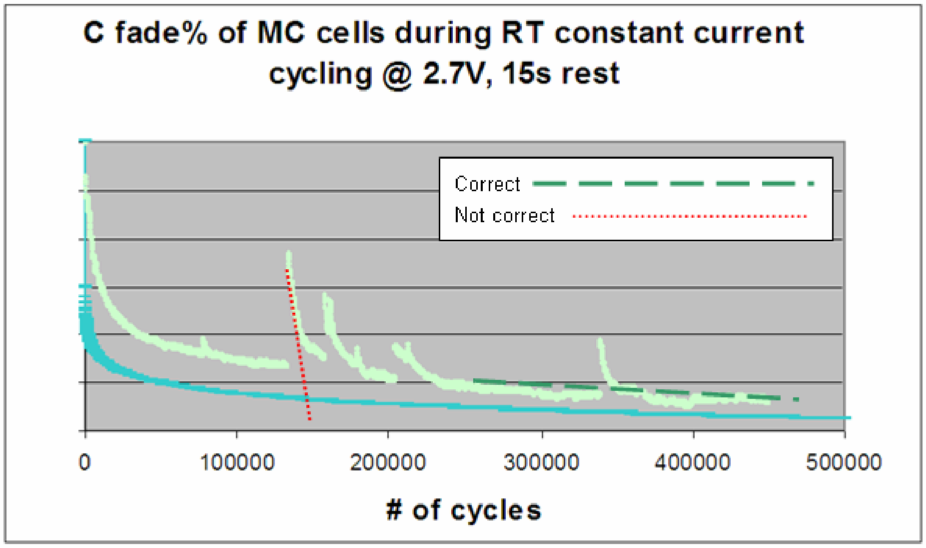
1. Because of the exponential behavior of the evolution of the capacitance during its first phase, the ELD calculation will give pessimistic results if executed when the module is operating in this domain. Once in the linear domain, the results will remain more constant and this is the only domain where accurate results can be obtained. This linear domain represents the majority of the system lifetime and is the most constant process value during the lifetime of the module.



ELD in function of the capacitance evolution domain

2. A phenomenon called recovery is observed. If the tension is interrupted on a capacitor after a long period of continuous usage (DC or voltage cycles), the measurement of the capacitance and the series resistance show a recovery as a function of the rest time without use.

    - The measured capacitance increases
    - The measured resistance decreases



Example of the influence of recovery phenomena on the capacitance evolution

For these two reasons, the level of confidence in the ELD value increases if the following point is taken into account:

- If the Capacitance C1 and C2 are much higher than the last recorded values, it is possible that a recovery occurred and the ELD is not relevant. Therefore, it is recommended to wait until the recovery has abated before executing another ELD estimate. This could take as many as 30000 or 40000 cycles.

6. Capacitance measurement

The capacitance of the module can be calculated by measuring time, voltage and current and applying the following equation:

$$C = \frac{i \cdot dt}{dU}$$

In order to obtain the higher quality of measurement, the current, voltage levels and the time must be clearly defined. As the temperature has an influence, the measurement should be done at a defined temperature range each time a measurement is taken. If not, the results will be affected.

The voltage and the internal temperature of the module are directly available from the taps on the module, but the current must be measured through an external sensor. The system controller must be able to handle all the data and compute the results.

7. Other parameters calculation

7.1. ESR

ESR can be measured by monitoring the voltage drop at the module when charging with a defined current:

1. At time t_0, read voltage: U_1
2. Apply calibrated step current Δi
3. At time $t_0+\Delta t$, record U_2

$$ESR = \frac{U_2 - U_1}{\Delta i}$$

The step current Δi and Δt must be defined. Since we are attempting to measure very low ESR values, the accuracy of the instrumentation performing the measurements must be appropriately high.

7.2. SOC

The state of charge of the module is directly proportional to the voltage and the capacitance of the module:

$$E = \frac{C \cdot V^2}{2}$$

Because of the dependency of the capacitance to the voltage, the measurement must be always carried out at a define voltage level, for example at nominal voltage.

7.3. SOH

For the state of health of the module the variations of the ESR and of the capacitance are the relevant parameters. The calculation of the ELD gives the most important information for the SOH of the module.

8. Summary

It is possible to obtain a general estimation of the lifetime of a series of capacitors in an application with a few simple measurements and calculations. The lifetime has to be compared against a set of predefined criteria most commonly the capacitance remaining in the module and the ESR of the module. The computation of lifetime estimation is prone to many sources of variation and error and; therefore, this procedure is recommended as a guideline only and does not actually predict the real lifetime. Transient environmental conditions can significantly affect lifetime and this must be monitored and accounted for by the user. Maxwell Technologies Inc. makes no guarantee of the predicted lifetime of the cells or modules by using the described procedure as it is very dependent upon operating conditions and measurement capability.

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