NESSCAP ULTRACAPACITOR

TECHNICAL GUIDE

2008

Nesscap Co., Ltd.

NESSCAP CO., LTD. (446-901) 750-8, Gomae-dong, Giheung-gu, Yongin-si, Gyeonggi-do, Korea, www.nesscap.com

About Ultracapacitors?

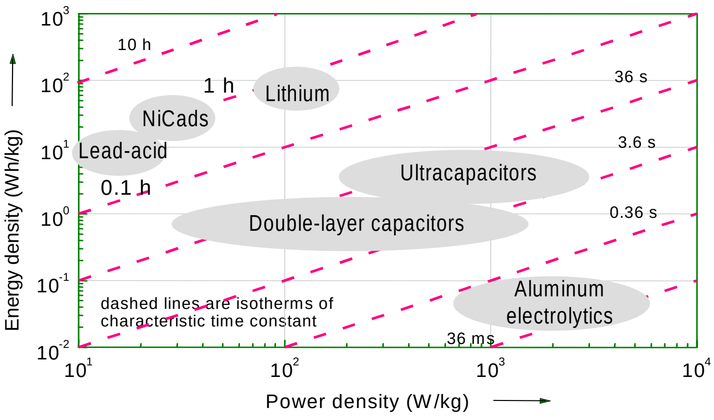
Enter the ultracapacitor, also known as a supercapacitor, Electric Double Layer Capacitor (EDLC), or pseudocapacitor. Ultracapacitors offer a shift in thought, circumventing the battery scramble, and instead attempt to elicit greater efficiency from existing power sources. With few even cognizant of its so far humble existence, the ultracapacitor rests on the fringe of awareness due to high price and manufacturability issues. However, the ultracapacitor enjoys boundless growth potential because it responds to key market and societal needs: it is environmentally friendly, helps conserve energy, and enhances the performance and portability of consumer devices. Ultracapacitors are also free from the characteristic battery problems of limited cycle life, cold intolerance, and critical charging rates.

Why Ultracapacitors?

Ultracapacitors are being developed as an alternative to pulse batteries. To be an attractive alternative, ultracapacitors must have higher power and much longer shelf and cycle life than batteries. By “much” is meant at least one order of magnitude higher. Ultracapacitors have much lower energy density then batteries and their low energy density is in most cases the factor that determines the feasibility of their use in a particular high power application.

Around for decades, a conventional electrolytic capacitor is an energy storage device that can be thought of basically as a container that gradually fills with electrical energy and then delivers it when needed in a sudden burst. Available just in the recent past, an ultracapacitor is a high-energy version of a conventional capacitor, holding hundreds of times more energy per unit volume or mass than the latter by utilizing state of the art materials and high-tech microscopic manufacturing processes. When fully charged, these robust devices deliver instant power in an affordable, compact package.

Long an enigma due to price—the bottom line— the advent of inexpensive, compact ultracapacitors, characterized by an exceptionally high surface area, excellent conductivity, and superior chemical and physical stability, heralds a new era of practical usage.



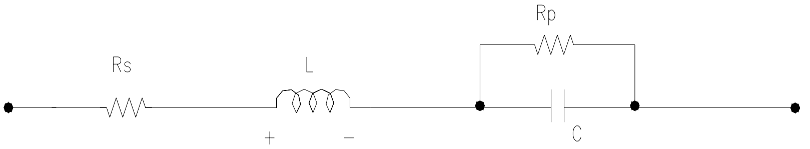
[Fig. 1] Power vs energy characteristics of energy storage devices

General Characteristics of Ultracapacitors As a Circuit Element

The same equivalent circuit used for conventional capacitors can also be applied to ultracapacitors.

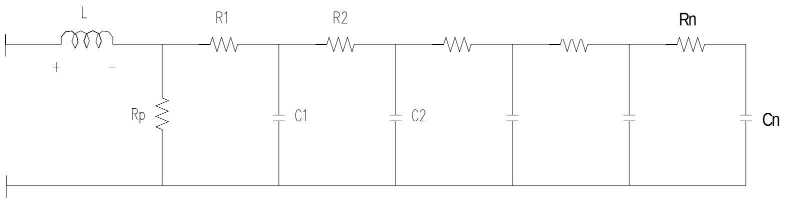
NESSCAP CO., LTD. (446-901) 750-8, Gomae-dong, Giheung-gu, Yongin-si, Gyeonggi-do, Korea, www.nesscap.com

The circuit schematic in [Fig. 2] represents the first-order model for an ultracapacitor. It is comprised of four ideal circuit elements, which include a capacitance C, a series resistor R_s, a parallel resistor R_p, and a series inductor L. R_s is called the equivalent series resistance (ESR) and contribute to energy loss during capacitor charging and discharging. R_p simulate energy loss due to capacitor self-discharge. It is often referred to as the leakage current resistance. Inductor L results primarily from the physical construction of capacitor and is usually small. However, it cannot be neglected in many applications, particularly those operating at high frequencies or subjected to hard switching.



[Fig. 2] The first-order circuit model of an ultracapacitor. Each of four circuit elements is ideal.

Resistor R_p is always much higher than Rs in practical capacitors. Thus it can often be neglected, particularly in high-power applications. In that case, the impedance of the [Fig. 2] circuit model is Z = R + i (2πfL-1/2πfC), where L is the inductance in [Henrys]. The impedance is purely resistive when 2πfL-1/2πfC = 0, or f = 1/2 $\pi(LC)^{1/2}$. This particular frequency is referred to as the resonance frequency of the capacitor. Thus, the impedance of circuit is simply the resistance at self-resonance. However, ultracapacitors exhibit non-ideal behavior, which result primarily from the porous material used to form the electrodes that causes the resistance and capacitance to be distributed such that the electrical response mimics tranmission line behavior. Therefore, it would be needed to use more general circuit shown in [Fig. 4] for representing the real ultracapacitor's electrical response.



[Fig. 3] The equivalent circuit of an actual ultracapacitor.

DC Behavior of Ultracapacitors

Ultracapacitors used in electric drivelines to load-label the battery experience large-steady (transient) direct currents (DC), much like the battery, rather than small amplitude, alternating current (AC) signals. The DC charge or discharge time (t_{disch}) of the capacitor is related to the fundamental characteristic frequency (f_{AC} in [Hz]) of the AC voltage on the capacitor by $t_{disch} \approx 1/4f_{AC}$. Hence for several to several tens of back-up time applications, the AC signal of most interest are lower than 10Hz.

In testing ultracapacitors, it is convenient to model them as a simple series RC circuit when inductive effects are unimportant. In this case, Q = CV, E = 1/2 CV^2 and $V_o - V = iR + (Q_o - Q / C)$, where Q is charge on the capacitor, V is voltage on capacitor, E is energy stored in the capacitor and Vo and Q_o are voltage and charge at t = 0, respectively.

The Measuring Condition of Electrical Performance

1. Charging and Discharging Method

An ultracapacitor can be charged from any DC power sources, DC power supply, battery or solae cell. There is no limitation in current and voltage within its maximum current and voltage rating. They can be referred to the specification sheet of each product. But you have to caution that the charging voltage does not exceed its rated voltage.

The time required for the constant current and constant resistance discharging are respectively represented by the equation (1) and (2) below:

Discharging time (t) of constant current discharge

$t=C \times ((V_0-V_1) / i$ ......(1)

Discharging time (t) of constant resistance discharge

$t=-CR\ln(V_1/V_0)$ ......(2)

where, t = discharging time (s), V_0 = initial voltage (v), V_1 = terminal voltage (v), i = current during back-up (A).

The above equations may not always be accurate, as the terminal down voltage must be considered after the start of discharge if load resistance or load current is present.

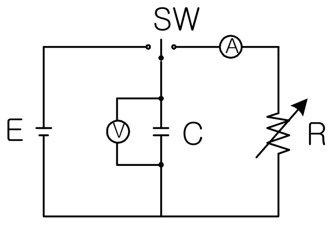
2. Capacitance

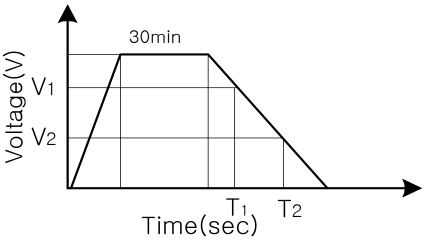
Charging is performed for duration of 30 minutes at rated voltage. Discharge use a constant current load device and measure the time for the terminal voltage to drop from V_1 to V_2 upon discharge at 1mA/F. The capacitance can be obtained by the following equation,

$$C = \frac{i \times (T_2 - T_1)}{V_1 - V_2} \text{ (F)}$$

Where, $V_1 = 0.7* V_R$, $V_2 = 0.3* V_R$ (V_R is rated voltage of a capacitor)

R : Constant electric current load





V : Voltmeter
A : DC Ammeter

[Fig. 4] Circuit diagram and charge/discharge profile to determine capacitance

3. ESR

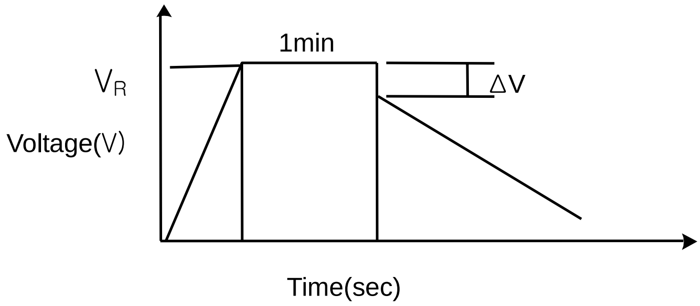
AC ESR is measured by 4-probe impedance analyzer at the following conditions.

Condition: Potentiostat mode, AC amplitude: 5mV, Frequency: 1kHz

DC ESR is measured by the following procedure.

1) Charging is performed by constant current followed by constant voltage charging
2) After reaching rated voltage, the voltage shall be hold at least 60 minute
2) Discharge current at 1mA/F
3) Reading of ∆V be measured
4) Internal resistance is calculated from the following formula

$$R = \frac{\Delta V\ (V)}{i\ (A)}\ (m\Omega)$$



[Fig. 5] Discharge testing for measuring DC ESR

4. Leakage current

The capacitor is charged with the rated voltage (4.6V) for 12~72hrs. Then, leakage current is measured by current measurement equipment.

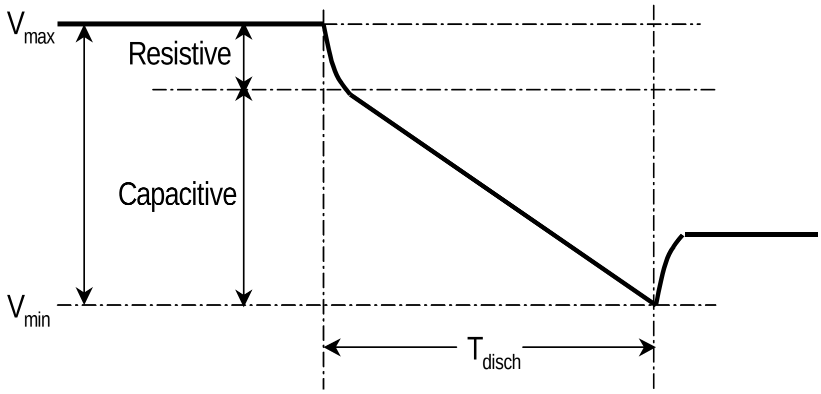
Polarity

Be sure to verify the polarity of the capacitor before use. If a reverse voltage is applied for a long time, capacitor lifetime is shortened and serious damage such as electrolyte leakage may occur. Furthermore, there may be leftover electric charge from capacitor testing that could damage other circuit components such as the low-withstanding voltage parts of semiconductors, etc.

Determining Method of Ultracapacitor Module for the Appropriate Application

An ultracapacitor's voltage profile has the capacitive and resistive component. This can be represented by dV = i (R+dt/C), where, dV is allowable change in voltage in [Volt], i is current in [Amp], R is ESR in [Ohm], dt is charge or discharge time is [sec], and C is capacitance in [Farads].

The number of ultracapacitor cells required can be determined by the system variables such as allowable change in voltage (max and min voltage), current (or power) and required duration time.



[Fig. 6] Discharge profile of an ultracapacitor

Connecting Capacitors in Series

Taking into consideration the possibility of an imbalance in the voltages across the capacitors, make sure that the voltage applied to each capacitor will not exceed the rated voltage. If the voltage balance breaks down, an overvoltage condition could result.

To prevent this from occurring, add a voltage-dividing resistor in parallel with each capacitor, allowing for the capacitor's leakage current. Always consider safety when designing equipment and circuits. Plan for worst-case failure modes such as short circuits and open circuits which could occur during use.

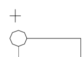
1) Provide protection circuits and protection devices to allow safe failure modes.
2) Design redundant or secondary circuits where possible to assure continued operation in case of main circuit failure.

Cell Voltage Equalization in a Series Stack of Ultracapacitors

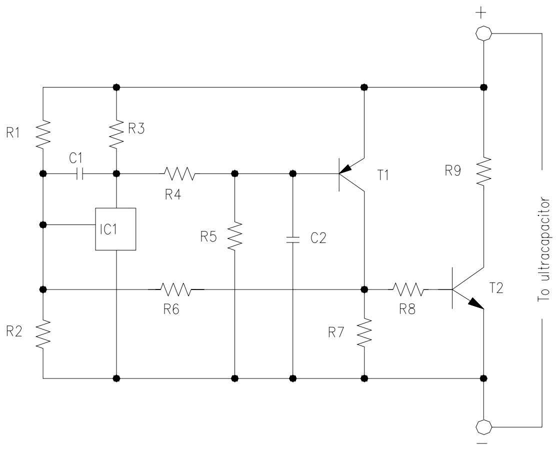
Many system applications require that capacitors be connected together, in series and/or parallel combinations, to form a "bank" with a specific voltage and capacitance rating. Because sustained overvoltage can cause an ultracapacitor to fail, the voltage across each cell in series stack must not exceed the maximum continuous working voltage rating of individual cells in the stack. The designer must either reduce the "rate of charge" being delivered to a cell, or completely stop charging a cell whose voltage approaches it's surge voltage rating.

The easiest way to reduce the current that's charging an ultracapacitor cell is to divert some of it around the cell. One such method employs a passive bypass component. The other, more complicated procedure uses an active bypass circuit. After the stack has been held at voltage for a period of time, voltage distribution then becomes a function of internal parallel resistance. The cells with higher leakage current should have lower cell voltages, and vice versa in a series stack of ultracapacitors.

One technique to compensate for variations in parallel resistance is to place a bypass resistor in parallel with each cell, sized to dominate the total cell leakage current. This effectively reduces the variation of equivalent parallel resistance between the cells. The active balancing circuit has an active switching



device, like a bipolar transistor or a MOSFET, connected in series with each bypass element ladder. The switches are controlled by voltage-detection circuits that only turn a switch “on” when the voltage across that particular cell approaches a value just slightly below the continuous working –voltage rating of the cell. This is called the bypass threshold voltage. [Fig. 4] depicts a typical block diagram of an active charging-current diversion circuit.



[Fig. 7] Block diagram of an active balancing circuit

Life-time

Ultracapacitors have a longer lifetime than do secondary batteries, but their life is still limited. During use, capacitance decreases and internal resistance rises. The lifetime of a Ultracapacitor is greatly affected by ambient temperature, applied voltage and operating current. By reducing these factors as much as possible, capacitor lifetime can be lengthened.

1. Operating Temperature Dependence

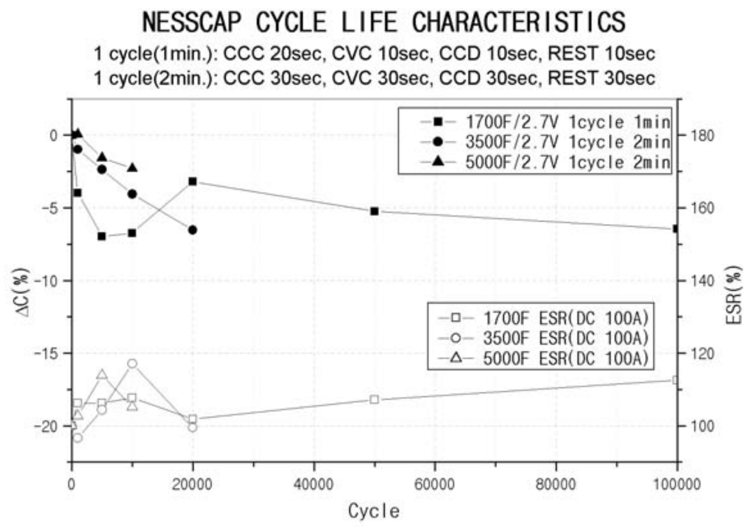
Capacitor life is affected by operating temperature. In general, lowering ambient temperature by 10°C will double the life of a capacitor. Use the capacitor at the lowest possible temperature under the maximum guaranteed temperature. Operation above the maximum specified temperature not only shortens capacitor life, but can also cause serious damage such as electrolyte leakage.

Verify the operating temperature of the capacitor by taking into consideration not only the ambient temperature and temperature inside the unit, but also the radiation from heat generating elements inside the unit (power transistors, IC’s, resistors, etc.) and self-heating due to ripple current. Be careful not to place heat-generating elements across from the capacitor on the opposite side of the PCB.

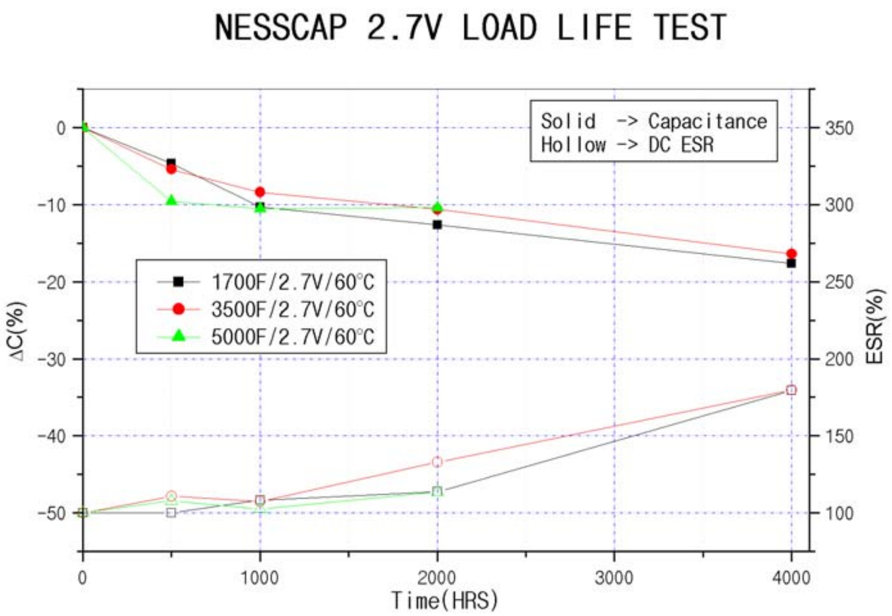
We usually use "high-temperature load life time" to measure the life time of ultracapacitor. For example, 1000 hours under full charging conditions at temp 70C is equivalent to 7.3 years of room temp (+25C) under normal use. Most of capacitor company says if the capacitance (F) decreases by 30% from the initial capacitance, the capacitor' life time is finished. In case of Ness Capacitors, the capacitance is decreased only 10~20% after 4,000 hours at 60C + full charging conditions, and thus we can say that Nesscap has more than 10 years (actually more than 20 years) life time with confidence.

2. Voltage Dependence

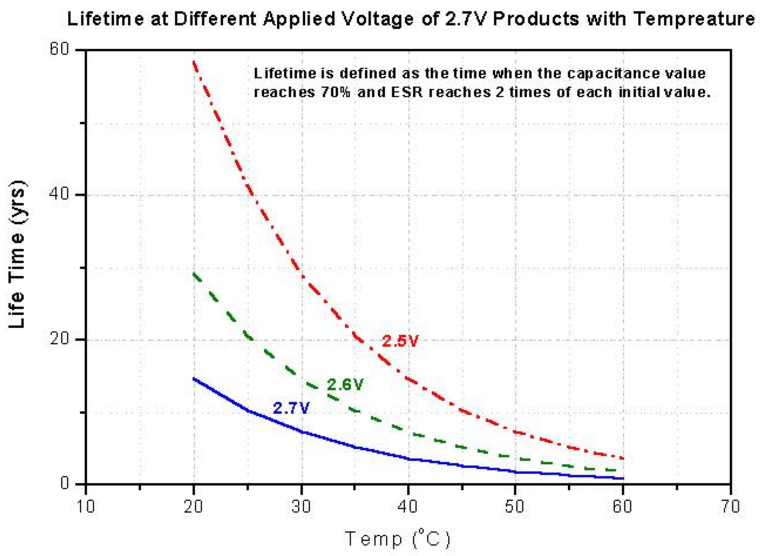
If a ultracapacitor is used at a voltage exceeding its rated voltage, not only is its lifetime shortened, but depending on the actual voltage, gas generated by electrochemical reactions inside the capacitor may cause it to leak or rupture.



[Fig. 8] Cycle life data based on actual measurement.



[Fig. 9] Load life data based on actual measurement.

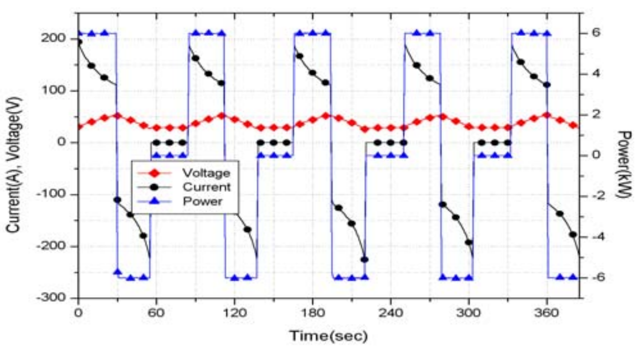


[Fig. 10] Expected life time based on actually measured load life

Applications of Ultracapacitors

Ultracapacitors benefit many applications, from those involving short power pulses, to those requiring low-power support of critical memory systems. Whether used alone, or with other power sources, ultracapacitors provide an excellent solution in a number of system configurations and high power applications such as cellular electronics, power conditioning, uninterruptible power supplies (UPS), industrial lasers, medical equipment, and power electronics in conventional, electric and hybrid vehicles.

Ultracapacitor permit faster acceleration, increases range, and extends battery life by freeing it from stressful high power tasks. In addition, ultracapacitor technology can now do load-leveling to extend the life of EV batteries and provide the high power essential for EV acceleration. For example, a vehicle might use this power burst to accelerate and climb a steep hill. Ultracapacitors can also absorb regenerative braking energy and thus limit the otherwise very high charging current to the battery.



[Fig. 11] 54V/175F NESSCAP ultracapacitor bank module and 6kW cycling data for 42V vehicle application

Ultracapacitors provide short-term support for Uninterruptible Power Supplies (UPS). With less energy storage capability than a battery, an ultracapacitor is not a viable substitute in UPSs as a long-term power source. However, as a short-term support for UPSs, its instant power and rapid response capability allows it to act as a bridge during power outages until an alternative source kicks in, such as a generator or other backup power supply. In addition, ultracapacitors can serve as a load-leveling function by absorbing power surges and spikes and then releasing clean quality power essential for precision high-tech equipment.

A properly installed ultracapacitors can extend the battery lifetime and improve the car audio performance, including reducing harmonic distortion in the low frequencies.

[Fig. 12] Applications of ultracapacitors