Letters

Long-Term Wide-Temperature Supercapacitor Ragone Plot Based on Manufacturer Datasheet

N. Reichbach, M. Mellincovsky, M. M. Peretz, and A. Kuperman

***Abstract*—Methodology for obtaining realistic supercapacitor (SC) Ragone from manufacturer datasheet only is presented in this letter, allowing to predict long-term wide-temperature SC power and energy performance for given terminal voltage limits. Analytical derivations are based on the simplified *RC* equivalent SC model, connected to a constant power element, taking into account manufacturer provided age and temperature parameter dependences. The main goal of the proposed approach is to allow practical energy engineer to quickly design a SC pack according to the desired long-term performance without performing further tests or requesting additional data. Simulation and experimental results are presented in order to validate the suggested methodology.**

***Index Terms*—Ragone plot, supercapacitor, temperature and age dependence.**

I. Introduction

Supercapacitor (SC) sizing is often accomplished according to nominal power and energy densities provided in the manufacturer's datasheet. Nevertheless, these values neglect device internal resistance as well as ageing and temperature dependences [1]–[4]. Moreover, discharge from rated voltage down to zero is assumed in nominal datasheet values, which is practically impossible since in power load applications terminal voltage decrease implies current escalation and must thus be limited. On the other hand, pushing upper voltage limit towards rated value leads to cycle life deterioration. Consequently, SC is usually cycled between two voltage levels, set according to these trade-offs, hence energy and power capabilities of the device must be calculated accordingly. This letter presents a methodology of creating realistic SC Ragone plots [5] based on manufacturer provided datasheet taking into account device losses as well as temperature and age dependences without considering transient phenomena such as the decay voltage associated to the self-discharge and redistribution, making possible to predict long-term, wide temperature range power and energy capabilities of a SC for given terminal voltage limits.

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N. Reichbach and A. Kuperman are with the Department of Electrical Engineering and Electronics, Ariel University, Ariel 40700, Israel (e-mail: reichbachim@gmail.com; alonku@ariel.ac.il).

M. Mellincovsky and M. M. Peretz are with the Department of Electrical and Computer Engineering, Ben-Gurion University, Beer-Sheva 8410501, Israel (e-mail: m.mellincovsky@gmail.com; morp@ee.bgu.ac.il).

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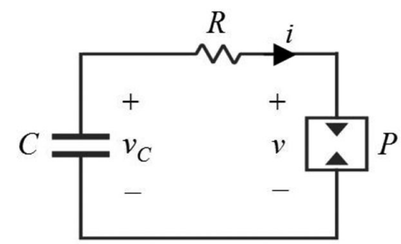

Fig. 1. SC connected to a power load.

II. Methodology

Consider a SC equivalent circuit, consisting of equivalent capacitance *C* and equivalent series resistance (ESR) *R*, connected to a positive constant power load *P* (cf., Fig. 1). Denote initial internal capacitance voltage as $v_C\left(0^-\right) = V_0$. Assuming that the device is resting prior to connection to the constant power load at $t = 0$, initial terminal and internal capacitance voltages are equal, i.e., $v\left(0^-\right) = V_0$. The discharge time is then given by [6]

$$t = C\left(2P\right)^{-1}\left(V_1^2 - v^2(t)\right) + RC\ln\left(V_1^{-1}v(t)\right), \qquad (1)$$

where

$$V_1 = v_C\left(0^+\right) = 0.5V_0\left(1 + \sqrt{1 - 4RP\left(V_0\right)^{-2}}\right) \qquad (2)$$

is the SC terminal voltage after the constant power load *P* was applied (note that internal capacitance voltage remains unchanged, $v_C\left(0^+\right) = v_C\left(0^-\right)$). The energy delivered to the load can then be expressed as

$$E(t) = P \cdot t = 0.5C\left(V_1^2 - v^2(t)\right) - PRC\ln\left(V_1 v^{-1}(t)\right). \qquad (3)$$

In general, initial SC voltage V_0 must be equal to or lower than manufacturer declared rated voltage V_R and may consequently be symbolized as

$$V_0 = \beta V_R \qquad (4)$$

with $0 < \beta \leq 1$. On the other hand, designating lower SC terminal voltage limit as

$$V_2 = \alpha V_0 = \alpha\beta V_R \qquad (5)$$

with $0 < \alpha \leq 1$, the energy delivered to the load a constant rate of P while swinging the SC terminal voltage from V_0 down to V_2 is given by

$$E(P)|_{\alpha\beta V_R}^{\alpha V_R} = \frac{C}{2}\left(\frac{\beta^2 V_R^2}{4}\left(1+\sqrt{1-\frac{4RP}{\beta^2 V_R^2}}\right)^2 - \alpha^2\beta^2 V_R^2\right) - PRC\ln\left(\frac{1}{2\alpha}\left(1+\sqrt{1-\frac{4RP}{\beta^2 V_R^2}}\right)\right). \quad (6)$$

The maximum value of constant power load that a SC is capable of supplying is limited by initial and final capacitor voltage. For $\alpha \geq 0.5$, the power capability is limited by [1]

$$P_{\mathrm{MAX}}^{\alpha > 0.5} = R^{-1}\alpha\,(1-\alpha)\,\beta^2 V_R^2. \quad (7)$$

If $P = P_{\mathrm{MAX}}$ is applied, the terminal voltage would instantaneously drop to $V_1 = V_2$ and no energy would be delivered to the load. Theoretical global maximum power is obtained for $\alpha = 0.5$ as

$$P_{\mathrm{MAX}}^{\alpha = 0.5} = (4R)^{-1}\beta^2 V_R^2, \quad (8)$$

instantaneously dropping terminal voltage from βV_R down to $\frac{1}{2}\beta V_R$, which is the highest possible initial voltage drop. Note maximum power capability provided by the manufacturers (so-called *matched impedance power*) is usually calculated according to (8) with $\beta = 1$ and hence has no practical use. For $\alpha \leq 0.5$, the maximum power is given by

$$P_{\mathrm{MAX}}^{\alpha < 0.5} = R^{-1}\alpha^2\beta^2 V_R^2. \quad (9)$$

Nevertheless, since maximum initial voltage drop is limited by $0.5\,\beta V_R$, in case of $\alpha \leq 0.5$ drawing maximum power necessary implies energy delivery.

For a given rated voltage, *E–P* relation (6) depends on α, β, *C* and *R*. The former two are selected by the designer according to application and energy-cycle life trade-off (increasing upper voltage limit shortens SC life while increasing its energy density). On the other hand, device capacitance and ESR are temperature and age dependent. These dependences (either estimated or manufacturer provided) should be combined with (6) in order to obtain a long term, wide-temperature range Ragone plot in order to provide the full picture of SC expected performance. In general, power and energy performance of a SC at beginning of life (BOL) would be higher than of a device at end of life. Similar conclusions may be drawn when comparing hot and cold temperature operations.

III. Example

Consider a 16.2 V, 61 F, 20 mΩ SC, operated with $\beta = 0.926$ and $\alpha = 0.5$, i.e., cycled from $V_0 = 15$ V down to $V_0 = 7.5$ V. Matched impedance power of the device is then 2813 W. Assuming Maxwell-provided capacitance and ESR dependence on cycle life and temperature (see [1, Figs. 11 and 12]), three-dimensional (3-D) Ragone plot, shown in Fig. 2, may be constructed, where each surface corresponds to a specific temperature (0 and −40 °C are shown; note that temperatures above 0 °C has negligible influence on device parameters). Alternatively, classic 2-D structure may be preserved while demonstrating a family of plots for each specific temperature, see Fig. 3.

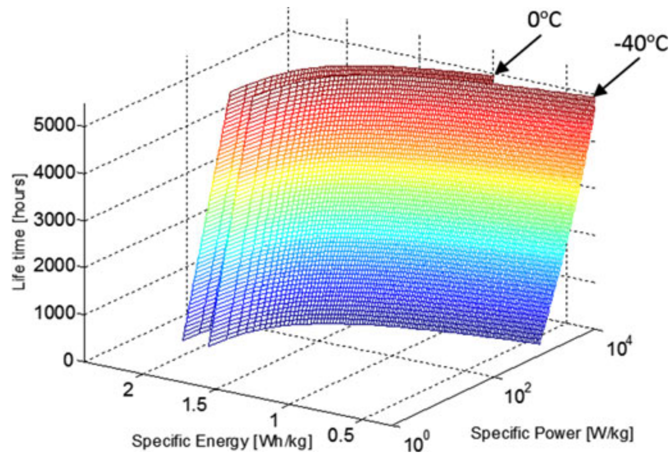

Fig. 2. Three-dimensional Ragone plot for different age and temperature conditions.

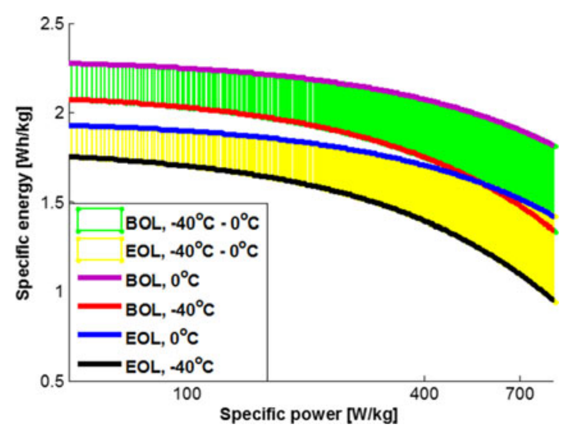

Fig. 3. Two-dimensional Ragone plot for different age and temperature conditions.

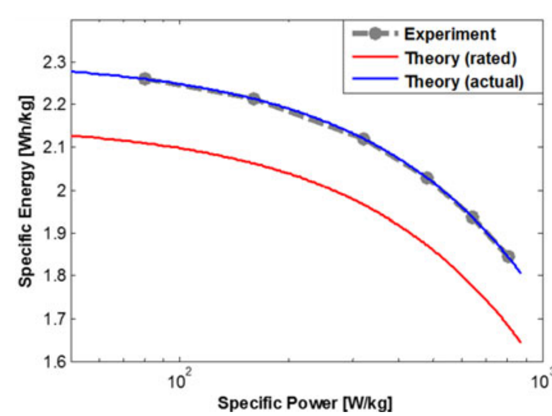

Fig. 4. Theoretical versus experimental Ragone plots at BOL, 25 °C.

In order to validate the presented methodology, a 16.2 V, 630 g BMOD0058-E016-B02 Maxwell SC at BOL with rated capacitance and ESR of 58 F and 22 mΩ, respectively, was used in the experiments. The device was discharged at several constant power rates (80–800 W range) from 15 down to 7.5 V (similar to the example above), at room temperature (circa 25 °C). Actual device capacitance and ESR were estimated prior to constant power discharge experiments as 61 F and 20 mΩ, respectively, by several charge-discharge tests. This should not be surprising since exploring the device datasheet reveals that parameter tolerances are given in $-0\%/+20\%$ range, hence the inaccuracy is acceptable [1]. The results are summarized in Fig. 4 along with theoretically estimated outcomes, calculated according to actual and rated SC parameters, respectively. As expected, experimental results overlap with actual parameters-related theoretically estimated Ragone plot and demonstrate performance superiority over rated parameters-related theoretically estimated Ragone plot. Consequently, rated-parameters related results may be considered as the worst case to be expected.

IV. Conclusion

Methodology of creating SC Ragone plots based on manufacturer datasheet was proposed, taking into account device losses as well as temperature and age dependent parameter variations. The approach allows predicting long-term wide temperature range power and energy performance of SC cycled between certain terminal voltage limits.

References

[1] M. Mellincovsky, A. Kuperman, C. Lerman, S. Gadelovits, I. Aharon, N. Reichbach, G. Geula, and R. Nakash, "Performance and limitations of a constant power fed supercapacitor," *IEEE Trans. Energy Convers.*, vol. 29, no. 2, pp. 445–452, Jun. 2014.

[2] N. Rizoug, P. Bartholomeus, and P. Le Moigne, "Study of the ageing process of a supercapacitor module using direct method of characterization," *IEEE Trans. Energy Convers.*, vol. 27, no. 2, pp. 220–228, Jun. 2012.

[3] D. Torregrossa, M. Bahramipanah, E. Namor, R. Cherkaoui, and M. Paolone, "Improvement of dynamic modeling of supercapacitor by residual charge effect estimation," *IEEE Trans. Ind. Electron.*, vol. 61, no. 3, pp. 1345–1354, Mar. 2014.

[4] D. Torregrossa, K. Toghill, G. Amstutz, G. Hubert, and M. Paolone, "Macroscopic indicators of fault diagnosis and ageing in electrochemical double layer capacitor," *J. Energy Storage*, vol. 2, pp. 8–24, Aug. 2015.

[5] A. Kuperman, M. Mellincovsky, C. Lerman, I. Aharon, N. Reichbach, G. Geula, and R. Nakash, "Supercapacitor sizing based on desired power and energy performance," *IEEE Trans. Power Electron.*, vol. 29, no. 10, pp. 5399–5405, Oct. 2014.

[6] T. Christen and M. Carlen, "Theory of Ragone plots," *J. Power Sources*, vol. 91, no. 2, pp. 210–216, Dec. 2000.