Considerations on the energy efficiency of a supercapacitive tank

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Abstract

Supercapacitors are electrochemical double layer capacitors, dedicated for the energy storage. Even if the energy density is still lower than that one of batteries, the supercapacitors are defined with a higher power density. The main advantage of that property is the time for charging and discharging the energy that can be strongly reduced. The limitation in the reduction of that time is defined by the series resistor of the supercapacitors, which defines the energy efficiency of the component. This has to be taken into account for the sizing of a supercapacitor tank, to identify the energy efficiency of that tank and to avoid any over-sizing of the storage system. This paper presents a method for the calculation of the energy efficiency of a supercapacitive bank, together with design criterion to size a supercapacitor tank taking into account the energy efficiency.

1 Introduction

Supercapacitors are components for energy storage. They propose high capacitance, from few farads to few thousand farads. Even if the amount of stored energy may not be compared with that one of classical batteries, the supercapacitors offer solutions in a lot of applications [1],[2].

There are mainly two application fields for supercapacitors. The first one is the use of supercapacitors as main energy source in each application where the energy and power requirements are compatible with the volume and the weight of the storage devices. This application for supercapacitors does correspond to a minority of cases.

The second main application for supercapacitors, corresponding to a majority of cases, is as energy buffers. The aim of using supercapacitors is here to consider them as storage components with high power density, associated to a main energy source. The target is then to minimize power constraints on the main energy source. This leads to association of supercapacitors with batteries, fuel cells, decentralized power network, compressed air storage systems, and many others…[3]

Even if supercapacitors are characterized by a high capacitance, the maximum voltage that can be applied across those components is still low (typically less than 2.5V). For most of the applications, the energy level stored in one single component is not enough. Depending on power and energy requirements, the number of needed supercapacitors has to be defined.

To find this number of supercapacitors, one must need to identify the level of energy that has to be stored. But this information is not sufficient. For a given amount of energy stored into a supercapacitive tank, it should be taken into account the energy efficiency of the supercapacitors themselves, and of course the efficiency of the associated power converter that interfaces the supercapacitive tank to a load. If the efficiency considerations on power converters are often taken into account, the energy efficiency of supercapacitors is generally not considered, and can lead to an under-sizing of the storage device.

The aim of the present paper is to present a method for sizing supercapacitive tanks, based on power and energy requirements. Then, the series resistor of those components will be taken into account, in order to identify their influence on the size of the supercapacitive tank.

2 Sizing a supercapacitive bank

2.1 Discharge voltage ratio and usable energy

Even if supercapacitors are not strictly capacitors from the technology and the construction point of view, the energy they can store is defined with the same law:

$$W = \frac{1}{2} C u_c^{\ 2} \tag{1}$$

Where W is the energy, C the capacitance and U_c is the voltage across the supercapacitor.

Typically, the maximum voltage across a supercapacitor is 2.5V. It has been also demonstrated that the capacitance of a supercapacitor is not constant, but is depending on the voltage across the component [4]. This leads to a no negligible increase of the total stored energy when the voltage across the supercapacitor is maximum. However, there are only few manufacturers that define the relation between the capacitance C and the voltage u_c in datasheets. For that reason, we will consider in this contribution that the capacitance C is constant, whatever the voltage u_c is.

For the use of the total stored energy (given when U_c is at its maximum level), the voltage across the component has to be decreased from its maximum allowed value to. This is not possible because the current provided by the supercapacitor should then be infinite for a given power level. For that reason, the minimum voltage when discharging the component has to be limited. As a consequence, all the energy stored in the component will not be used. It is then necessary to define the parameter d, that is the ratio between the minimum allowed voltage U_m for the discharging, and the maximum voltage U_M that defines a full charging of the component. The parameter d is expressed in percent and is called discharge voltage ratio:

$$d = \frac{U_m}{U_M} 100 \tag{2}$$

Under that condition, the usable energy W_u that a supercapacitor can provide is defined par the equation:

$$W_u = W_M \left[1 - \left(\frac{d}{100} \right)^2 \right] \tag{3}$$

The usable energy is a function of the total stored energy W_M and of the voltage discharge ratio d. As an example, if d=50%, then W_u will be 75% of the total stored energy W.

Knowing the needed usable energy, the number N_s of supercapacitors is easy to identify:

$$N_s = \frac{2W_u}{CU_M^2 \left[1 - \left(\frac{d}{100} \right)^2 \right]} \tag{4}$$

2.2 Power and Energy requirements

To size a supercapacitive bank, which means to identify the number of needed supercapacitors, it is required to know three parameters: the capacitance of the components, the value of the voltage discharge ratio that will be used, and the value of the needed usable energy.

The usable energy is not a parameter that is always defined in various applications [5]. If most of cases, power profile requirements are only defined, and the usable energy has to be identified thanks to this power profile, as it is shown in Figure 1.

On the left waveform a particular power profile is shown, corresponding to an application where supercapacitors have to provide such a power. As it appears on that profile, the mean power is 0W. The aim of such an application is to minimize the power constraints on an energy source, which has only to provide a constant mean power. All the power fluctuations have to be assumed by the supercapacitive tank. The power profile shown on the left frame of Figure 1 is as consequence part of the total power needed by a special load, that supercapacitors have to provide.

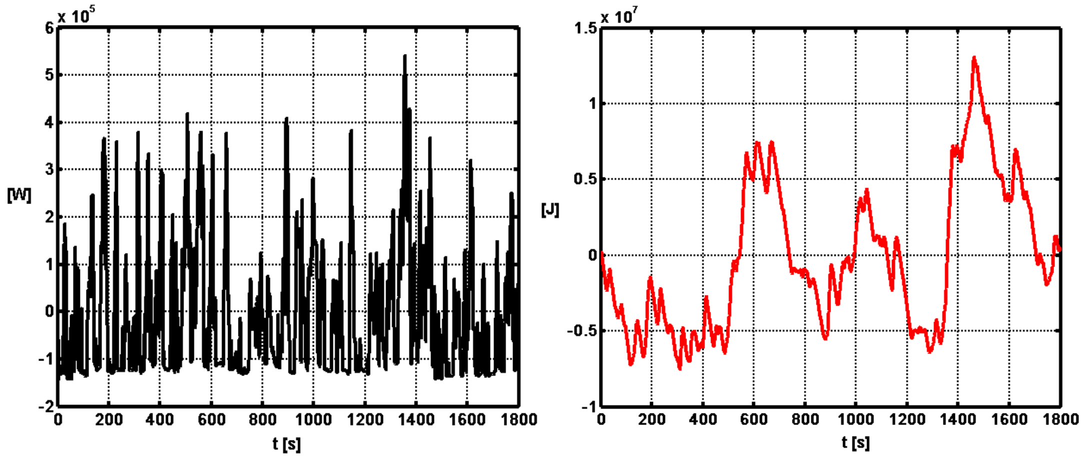

Figure 1 : Sizing a supercapacitive tank thanks to power requirements

As the main equations we have defined for sizing a supercapacitive tank are dealing with energy and not power, it is needed to deduce the needed usable energy from the power profile. This is easily done by numerical or formal integration of the power, which gives directly the energy profile associated with a given power profile.

The result of such integration for the considered example is shown on the left frame of Figure 1. This shows in this example that the supercapacitive bank has to provide or absorb energy, depending on the power requirements. It should be noticed that as the mean power that the supercapacitive tank has to provide is 0W, then the balance of energy is 0Wh. But between the beginning and the end of the power profile, the supercapacitive tank should be able to store 195Wh and to provide 3.64kWh.

The sum of these two energies defines the usable energy that has to be stored into the supercapacitive tank:

$$W_u = 0.195\text{kWh} + 3.64\text{kWh} = 3.835\text{kWh} = 13.8\text{MJ} \qquad (5)$$

2.3 Sizing of the supercapacitive tank

Knowing the needed usable energy that the supercapacitive bank has to provide, and thanks to the equation (4), it is then easy to identify the number of supercapacitors. Regarding the example considered in the previous section, different sizing results are given in Table 1.

W_u=13.8MJ, C=1800F, U_M=2.5V

N_s	d (%)	Volume (m^3)	Weight (kg)	W (J)
3272	50	0.98	1308	17.47
3834	60	1.15	1533	20.47
4811	70	1.44	1924	25.69

Table 1: Number of supercapacitors

Those results are given for supercapacitors that are characterized by a 1800F capacitance. They are established for three different values of the voltage discharge ratio d. For each possible sizing, the number of supercapacitors is given, with the corresponding volume and weight of the resulting supercapacitive bank. It is also given the total amount of stored energy that has to be compared to the needed usable energy.

Of course, the choice of d=50% leads to the most reduced number of supercapacitors, and the usable energy is 75% for the total stored energy.

On another hand, the choice of d=70% leads to an increased number of supercapacitors compared to the choice of d=50% (47% more supercapacitors). In this case, the usable energy is only 51% of the total stored energy. This has of course a consequence on the price of the supercapacitive tank, but leads however to few advantages regarding the versatility on the energy management because of the over-sizing of the supercapacitive tank: in case of an abnormal energy demand of the load it is possible to decrease the parameter d under 70% to request to a punctual and unforeseen need in energy. It should also been noticed that regarding the power and energy profiles defined in Figure 1, the size and the volume of the supercapacitive tank in the case where d=50% are limited [6].

3 Energy efficiency of a supercapacitor

3.1 Introduction

Even if the method presented for sizing a supercapacitive tank takes into account the necessary limitation of voltage variation across the supercapacitors, it should also be taken into account the energy efficiency of those components because all the usable energy cannot be transferred to the load, due to the internal series resistor of the supercapacitors. It has then to be considered that internal losses in the supercapacitors are produced during their discharging in order to eventually increase their number to satisfy the demand in usable energy. Of course the efficiency during the charging procedure has also an importance, as it has been described in [7].
In other words, the supercapacitive tank has to be over-sized in order to be able to provide the needed usable energy taking into account the losses into the tank.
Two cases will be considered in this contribution: the exponential discharge because a large majority of supercapacitor manufacturers use this discharge method to characterize their components, and the constant-current discharge because the current for discharging the supercapacitors is always controlled by the power converter which interfaces the supercapacitive tank and the load, and corresponds to a large range of applications.

3.2 Exponential discharge

In most cases, supercapacitor manufacturers use this particular discharge in order to characterize the efficiency of their components, even if that discharge does not correspond to the real case of use of a supercapacitor where the discharging current is generally controlled with a power converter.
The principle of the exponential discharge is first to consider the simple supercapacitor model shown in Figure 2, constituted of an ideal capacitor C and its internal series resistor R_s.

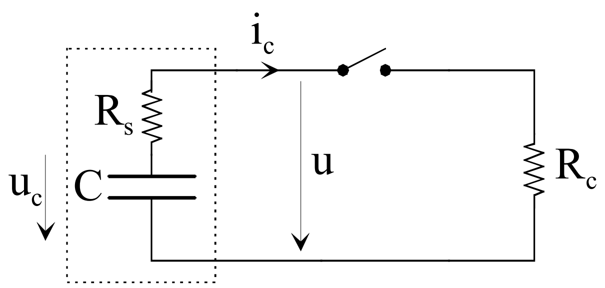

Figure 2 : Exponential discharge

It is first needed to identify the value of the capacitance C, and the value of the resistor R_s. Once those two parameters are known, it is easy to deduce the energy stored into the supercapacitor from the equation (1) when the voltage u_c is at its maximum value U_M, when no load is applied across the supercapacitor (I_c=0A).
Then, the supercapacitor is unloaded into the resistor R_c. The ratio between the energy dissipated into R_c and the energy provided by the capacitor C defines the energy efficiency of the supercapacitor in the case of an exponential discharge.

In order to formalize this procedure, few equations have to be defined. The first one defines the variation of the voltage u_c across C, from its full state of charge (Maximum voltage U_M):

$$u_c = U_M e^{-\frac{t}{(R_s+R_c)C}} \tag{6}$$

The supercapacitor will be considered as discharged when the voltage across C reaches the minimum voltage defined by the voltage discharge ratio:

$$U_M \frac{d}{100} = U_M e^{-\frac{T_{ch}}{(R_s+R_c)C}} \tag{7}$$

This last equation leads to the definition of the duration for the discharging of the supercapacitor from the maximum voltage U_M to the minimum voltage $U_M d/100$:

$$T_{ch} = -\left(R_s + R_c\right) C \ln \frac{d}{100} \tag{8}$$

To define the energy efficiency, the energy dissipated inside of the resistor R_c must be identified. This first step is to identify the power dissipated by Rc:

$$P_{R_c} = R_c i_c^2 = \frac{R_c}{\left(R_s + R_c\right)^2} U_M^2 e^{-\frac{2t}{(R_s+R_c)C}} \tag{9}$$

The energy dissipated in R_c is obtained by integration of the power:

$$W_{R_c} = \int_0^{T_{ch}} P_{R_c} dt = W_M \frac{R_c}{R_s + R_c}\left[1 - \left(\frac{d}{100}\right)^2\right] \tag{10}$$

As a result, the energy efficiency of a supercapacitor in the case of an exponential discharge from the maximum voltage U_M to the minimum voltage $U_M d/100$, is defined by the ratio between the energy dissipated by the resistor R_c and the usable energy provided by the capacitor C defined by the equation (3):

$$\eta_r = \frac{W_{R_s}}{W_u} = \frac{R_c}{R_s + R_c} \tag{11}$$

The energy efficiency of the exponential discharge varies from 100% (R_c>>R_s) to 0% (R_c<<R_s).

3.3 Current controlled discharge

The current controlled discharge of a supercapacitor is closer to the real use of a supercapacitor than the exponential discharge, because in most cases a power converter is associated to it as presented in Figure 3. The aim is to compensate the voltage variation on the supercapacitor during its discharging to apply a constant voltage to the load. As a result, the supercapacitor discharging current i_c is controlled. Various current profiles can be imagined, to obtain various discharge power profiles depending on the application. But the most general current profile is a constant current, that will be considered in this contribution [6]. In this case, it should be noticed that the associated discharge power profile is linearly decreasing. The voltage across the resistor R_c is then not constant, but also decreasing.

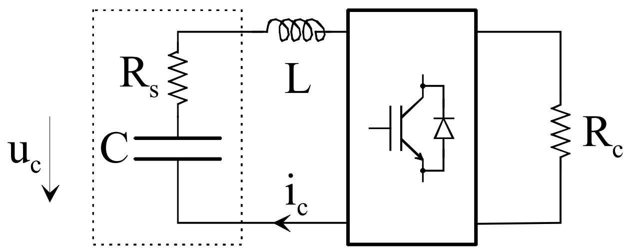

Figure 3 : Current controlled discharging

To compare the energy performances of the discharge with a constant current, the equations that have to be defined will be obtained by following the same procedure than the exponential charge.
The first equation defines the variation of the voltage u_c across C, from its full state of charge (Maximum voltage U_M):

$$u_c = U_M - \frac{1}{C} i_c t \tag{12}$$

The supercapacitor will be considered discharged when the voltage across C reaches the minimum voltage defined by the voltage discharge ratio:

$$U_M \frac{d}{100} = U_M - \frac{1}{C} i_c T_{ch} \tag{13}$$

This last equation leads to the definition of the duration for the discharging of the supercapacitor from the maximum voltage U_M to the minimum voltage $U_M d/100$:

$$T_{ch} = C \frac{U_M}{i_c} \left(1 - \frac{d}{100}\right) \tag{14}$$

To identify the energy efficiency, the losses into the internal series resistor R_s must be identified. The first step is to identify the power dissipated by R_s:

$$P_{R_s} = R_s i_c^{\,2} \tag{15}$$

The energy dissipated in R_s is obtained by integration of the power:

$$W_{R_s} = \int_0^{T_{ch}} P_{R_s} dt = R_s C i_c U_M \left(1 - \frac{d}{100}\right) \tag{16}$$

As a result, the energy efficiency of a supercapacitor, discharged with a constant current from the maximum voltage U_M to the minimum voltage $U_M d/100$, is defined by the ratio between the usable energy provided by the supercapacitor C minus the energy dissipated by the resistor R_c(which represents the energy transmitted to the power converter), and the usable energy provided by the capacitor C defined by the equation (3). This energy efficiency can be expressed as a function of the discharging current i_c, or as a function of the duration T_{ch} for the discharge:

$$\eta_i = \frac{W_u - W_{R_s}}{W_u} = 1 - 2R_s \frac{i_c}{U_M} \frac{100}{100+d} = 1 - 2R_s C \frac{1}{T_{ch}} \frac{100-d}{100+d} \tag{17}$$

The efficiency of the discharge with a constant current varies from 100% (reduced values of i_c and huge value for T_{ch}) to 0% (extreme values of i_c and strongly reduced value for T_{ch}).

3.4 Comparison and discussion

The efficiency of the exponential and constant current discharge, respectively given by the equations (11) and (17) are not easy to compare, because of the difference on their formulation together with the different type of parameters which influence the efficiency.
For the exponential discharge, the two main parameters that define the efficiency are the values of the series resistor R_s regarding the resistor R_c.
For the constant current discharge, the main parameters that define the efficiency are of course the value of R_s, and the discharge current i_c which defines also the time T_{ch} allowed for the discharge.
In order to compare the efficiency of these two type of discharge, we define the following procedure:

- We consider a 1800F/2.5V supercapacitor, with an internal series resistor R_s=1mΩ.
- We consider a voltage discharge ratio d=50%. When discharging, the minimum voltage across the supercapacitor will be the half of the initial maximum voltage U_M.
- We consider the time for discharge T_{ch} as the main and common parameter between the two types of discharge.

- From the time for discharge T_{ch}, we will determine:
  ⇒ The value of R_c that gives the time T_{ch} from the equation (8), and then the efficiency η_r for the exponential discharge from the equation (11).
  ⇒ The value of i_c that gives the time T_{ch} from the equation (14), and then the efficiency η_i for the constant current discharge from the equation (17).

The results of that comparison are given on the curves in Figure 4b, for T_{ch} varying from 2s (R_c=0.6mΩ or I_c=1125A) to 1000s (R_c=0.8mΩ or I_c=2.25A).

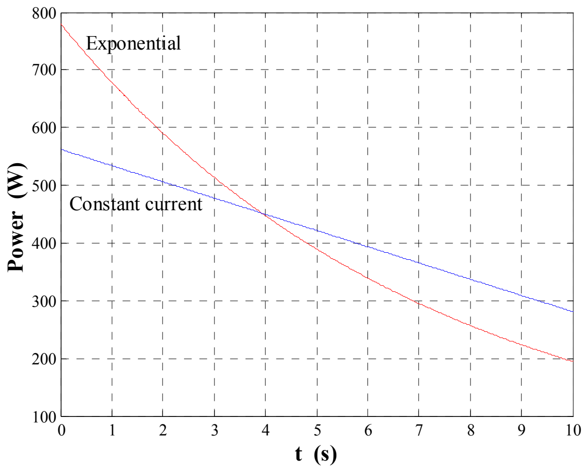

Figure 4a: Power profiles

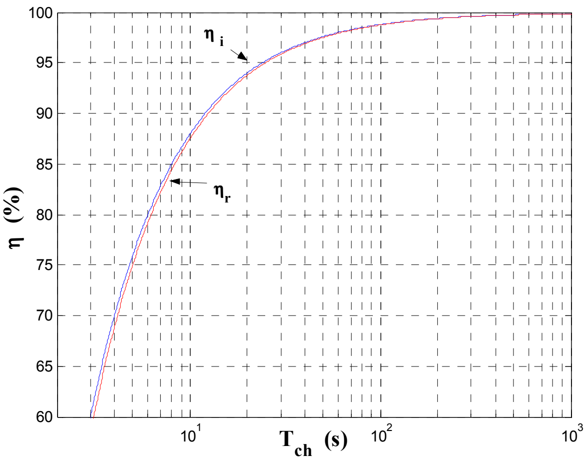

Figure 4b: Efficiency

Figure 4 : Comparison of the exponential and the constant current efficiencies

The first comment is that the efficiency decreases strongly when the time for discharge is low. For the considered internal resistance value (R_s=1mΩ), the time for discharge should be kept over 6s to maintain the efficiency higher than 80%.

The efficiency of the exponential discharge is quite similar to the efficiency of the constant current discharge. This confirms that the characterization of the energy efficiency with an exponential discharge leads to coherent results. As a complementary comparison, we give in Figure 4a the power profiles of the exponential and constant current discharges, obtained for the particular case where T_{ch} is 10s:

$$T_{ch} = 10s \qquad \left[\begin{array}{ll} R_c = 7m\Omega & \eta_r = 87.52\% \\ i_c = 225A & \eta_i = 88\% \end{array}\right. \tag{18}$$

It should be noticed that even if the power profiles are not identical, their mean values during the whole discharge is the same.

This result is only to be used for the discharge of supercapacitors, and certainly not for their charge, where the exponential charge leads to poor efficiency compared to the constant current charge [7].

4 Sizing a supercapacitive bank taking into account the energy efficiency

4.1 Main equations

Regarding the sizing of a supercapacitor tank taking into account power and energy requirements, the previous results on the efficiency show that it should also be taken into account the efficiency of the supercapacitors, because part of the energy stored into those component will be lost during the discharging.

The Figure 4 shows that the efficiency cannot be considered as unity in the range of T_{ch}=10s to T_{ch}=10s, which is typically the range of time discharge needed in applications with supercapacitors. It has then to be defined how to increase the number of supercapacitors of the supercapacitive tank, in order to be able to provide the needed usable energy independently from the losses into the components.

Knowing the energy efficiency of the supercapacitors thanks to the equations (11) and (17), it is then easy to identify the real usable energy $W_{\eta u}$ to be stored into the supercapacitive tank for a given usable energy W_u needed for a given application. The equations that define the real usable energy $W_{\eta u}$ taking into account the efficiency are given in the following equations for the general case, together with the cases of the exponential and constant current charge:

$$W_{\eta u} = \frac{W_u}{\eta} = \frac{W_M}{\eta}\left[1-\left(\frac{d}{100}\right)^2\right]$$

$$\left[\begin{aligned} & W_{\eta_r u} = \frac{R_s + R_c}{R_c} W_M \left[1-\left(\frac{d}{100}\right)^2\right] \\ & W_{\eta_r u} = \frac{W_M\left[1-\left(\frac{d}{100}\right)^2\right]}{\left(1-2R_s\frac{i_c}{U_M}\frac{100}{100+d}\right)} \end{aligned}\right. \qquad (19)$$

It is then easy to define the real number $N_{\eta s}$ of supercapacitors needed for an application, taking into account the efficiency of the supercapacitive tank. This increased number of supercapacitors is the ratio between the number of supercapacitors in case of no losses into the components, and the efficiency.

$$N_{\eta s} = \frac{2W_{\eta u}}{CU_M^2\left[1-\left(\frac{d}{100}\right)^2\right]} = \frac{N_s}{\eta} \qquad (20)$$

4.2 Comparison and discussion

In order to identify the way a supercapacitor tank has to be over-sized to take into account the energy efficiency, we consider the following example:

- The supercapacitive tank has to be designed to provide a usable energy W_u equal to 1MJ.
- The supercapacitors are 1800F/2.5V, with an internal series resistance R_s=1mΩ.
- The allowed duration for discharge W_u=1MJ from the supercapacitive tank is T_{ch}=10s, corresponding to a typical time of discharge for a supercapacitive tank.

The sizing results are given in Table 2, for various voltage discharge ratio (d=50%, 60% and 70%), both for the exponential and the constant current discharge.

W_u=1MJ, C=1800F, U_M=2.5V, R_s=1mΩ, T_{ch}=10s

	d (%)	η (%)	$W_{\eta u}$(MJ)	N_s	$N_{\eta s}$	Ratio (%)
Exponential	50	87.52	1.14	237	270	13.92
Constant current		88	1.13		269	13.5
Exponential	60	90.8	1.1	277	305	10.10
Constant current		91	1.09		305	10.10
Exponential	70	93.57	1.068	348	372	6.89
Constant current		96.64	1.067		372	6.89

Table 2 : Sizing taking into account the energy efficiency

For each considered cases are given the energy efficiency, the real usable energy $W_{\eta u}$ that has to be stored, the number of needed supercapacitors N_s in case of no loses, and the number of needed supercapacitors $N_{\eta s}$ when the energy efficiency is taken into account. Finally, the ratio of over-sizing is given, which represents the ratio between the real and the ideal number of supercapacitors.
It appears that the number of supercapacitors has to be increased when the voltage discharge ratio is decreased. The choice of d=70% is not finally a bad choice, because even if such a supercapacitive tank is basically over-sized, the added over-sizing for taking into account the losses does not lead to a strong increase of the number of supercapacitors, which is not the case for d=50%.
It should be also noticed that the difference of sizing between the exponential and the constant current charge does not lead to a significant difference of supercapacitor number for each different value of d. However, we insist on the fact that this study is only about discharge of supercapacitors. In the case of supercapacitors charge with exponential or constant current charge, the difference is strongly higher.

5 Conclusion

A method for sizing a supercapacitor tank has been presented, based on power and energy requirements.
This method is not only based on the power and energy a supercapacitive tank has to provide to a load. It takes into account the energy efficiency of the supercapacitors that are used.
Depending mainly on the value of the internal series resistor of the supercapacitors, the number of supercapacitors has to be increased to compensate their internal losses. But, regarding the considered cases (discharge of the supercapacitors), this does not lead to a strong over-size of the storage tank.
The main equations that can be used for such a sizing have been defined, regarding two particular discharge profiles: the exponential discharge and the constant current discharge.
This theoretical study is actually under experimental validation, with a complementary study of new discharge profile such as the discharge with a constant power.

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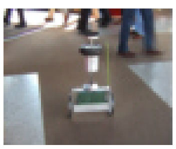

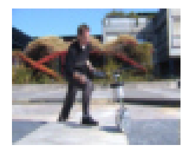

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