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Energy Storage Systems for Electric Vehicles: Performance Comparison based on a Simple Equivalent Circuit and Experimental Tests

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Abstract

The decision to select the most suitable type of energy storage system for an electric vehicle is always difficult, since many conditionings must be taken into account. Sometimes, this study can be made by means of complex mathematical models which represent the behavior of a battery, ultracapacitor or some other devices. However, these models are usually too dependent on parameters that are not easily available, which usually results in nonrealistic results. Besides, the more accurate the model, the more specific it needs to be, which becomes an issue when comparing systems of different nature. This paper proposes a practical methodology to compare different energy storage technologies. This is done by means of a linear approach of an equivalent circuit based on laboratory tests. Via these tests, the internal resistance and the self-discharge rate are evaluated, making it possible to compare different energy storage systems regardless their technology. Rather simple testing equipment is sufficient to give a comparative idea of the differences between each system, concerning issues such as efficiency, heating and self-discharge, when operating under a certain scenario. The proposed methodology is applied to four energy storage systems of different nature for the sake of illustration.

Keywords: energy storage, battery model, internal resistance, self-discharge.

1 Introduction

The battle for being the most competitive energy storage technology to be used in electric vehicles (EV) is one of the key issues for the industry [1][2]. This aspect is critical to both car companies, who integrate energy storage systems (ESS) in vehicles, and to the researchers and R&D companies who develop them, so that their research proves successful.

From the point of view of the final manufacturer of the EV, considered as an integrator of technologies (and even considering him as the designer of the full equipment), it is not easy to decide which is the most appropriate energy storage technology for their application [1][3]. It is not only a matter of power/energy levels design, but also of considering the number of cycles and the type of cycling the ESS will face during the operation of the system. The decision to select an ESS must comprise a wide range of specifications to define it properly. In fact, some mathematical models are considered to study the behaviour of ESS in terms of electrical, mechanical and thermal stresses under certain working conditions. Obviously, the more accurate and complete the model is, the more information can be obtained from it. The case of the batteries is especially significant in this sense, since their behaviour have a quite complex relationship with the electrical and thermal variables, resulting in a non-linear dynamic model that depends even of the lifetime and the history of the battery.

Several research groups and companies have developed accurate and very complex models for batteries [4]-[7]. After analysing different battery models, the authors of this paper have realized that many of the model parameters are rather difficult to determine. In some cases, these parameters are so operation-point-dependent that they cannot be fixed with reliability [8][9]. An interesting line of thought in this sense is the following: batteries cannot be successfully compared by means of their electrical and thermal models, since the conditions and assumptions made during the development of those models are not the same, and the parameters dependence is too strong to ensure the accuracy of the comparison. Therefore, when trying to select an ESS for a specific EV, it is worthless to put a lot of effort in such complicated models to compare different technologies, since the results will not provide a trustful assessment.

As an alternative methodology, the usage of a simple well-known electric model is proposed by the authors. The parameters of this model may be easily obtained from a bunch of laboratory tests. Despite its limitations, this model is accurate enough to get practical information in order to select the most suitable ESS. The results obtained from this model-based comparison should be completed with additional information regarding power and energy densities (in terms of mass and volume), together with information concerning the cost of each energy storage device.

This paper deals with several types of energy storage devices such as batteries (lead-acid and NiMH), ultra-batteries, ultra-capacitors, and even flywheels, which are being considered as a feasible and competitive alternative for some large vehicles [10][11].

In this paper, a simple methodology to compare ESS based on laboratory tests will be presented. The tests may be performed with just a few elements (modules or cells) of each ESS taken into consideration. The testing equipment will also be briefly described, as well as the specific tests required to ensure reliable results, depending on the application to be carried out by the ESS. Laboratory experimental results regarding ESS of different nature will also be described.

2 Electrical equivalent to compare the performance of ESS of different nature

When comparing ESS for hybrid and electric vehicles, efficiency and heating are two critical parameters. The former is directly related to the autonomy and the aging of the system, which are nowadays the bottlenecks for electromobility [2]. A more efficient ESS will satisfy the demanded power consuming less stored energy, so the autonomy will be increased. In other words, given two batteries with the same rated capacity, the most efficient one will have more available capacity than the less efficient one.

Overload capacity is quite an interesting feature, strongly related to heating. In EVs, it allows for the ESS to temporarily give/absorb power peaks, improving the performance of the vehicle (acceleration capacity, regenerative braking, and so on). A less self-heating ESS will be able to exchange more power with the powertrain with less cooling requirements. Likewise, given a fixed demand of power, the less self-heating device will work at lower temperature, which will improve its aging and increase its useful life. Besides, a device with higher overload capacity will reduce the size of the ESS and consequently the total cost.

Both efficiency and heating are a direct consequence of the internal losses within the EES. The higher these losses, the lower the efficiency and the worse the self-heating. Therefore, it is undoubtedly interesting to compare ESS taking the internal losses as a basis for comparison, at least in a first stage.

To do so, a simple and well-known but effective electrical equivalent circuit may be used. This equivalent must account for the available capacity, the internal resistance, and the self-discharge effect of the ESS. The proposed equivalent, shown in Fig.1, is arguably the most conventional equivalent circuit for batteries and other energy storage devices. The key parameter to evaluate both efficiency and self-heating is the internal resistance, responsible for the vast majority of the internal losses within the ESS.

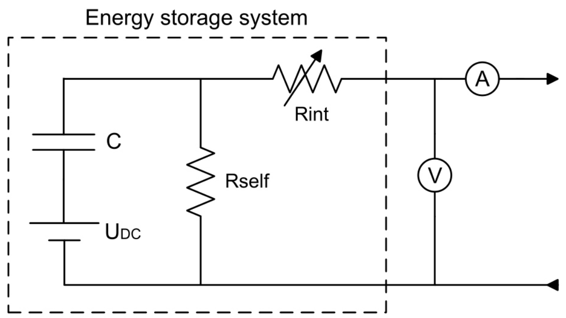

Figure 1: Electrical equivalent circuit for ESS comparison purposes.

The electrical model of Fig.1 comprises three basic parameters, which can be easily determined by the tests described in this paper:

- Stored energy or capacity, represented by a voltage source U_{DC} and a capacitance C in Fig.1. The voltage source represents the non-exchangeable energy, while the capacitor voltage depends on the energy stored.
- Self-discharge resistance, represented by a parallel resistance R_{self}.
- Internal resistance, represented by a variable series resistance R_{int}, and main responsible for the efficiency, voltage rise/drop and heating.

A fourth variable should be taken into account: the life-cycle of the ESS, especially important in batteries. The life-cycle will affect all the other three parameters, worsening the performance of the ESS as it ages. However, deep-cycle testing is beyond the scope of this paper, since the time needed to perform the necessary tests is considerable. In this sense, the authors will just consider the information provided by each ESS manufacturer.

It is important to note here that the internal resistance is modelled as a variable resistor in the equivalent circuit. This is necessary, since some ESS such as batteries usually show a non-linear behaviour regarding internal losses and self-heating.

2.1 Laboratory tests and parameters determination

Once the equivalent circuit has been established, its parameters must be calculated. To do so, two simple laboratory tests are proposed here.

2.1.1 Internal resistance test

The internal resistance R_{int} is rarely provided by the manufacturer of a given ESS. The literature is full of methods to calculate it, but they are either simulation-based [12] or too complex [13] for the purposes of this study. Other methods are specifically developed for on-line testing [14], which is neither the purpose of this work.

The proposed method is quite simple. It is based upon an energy balance during a symmetric charge/discharge cycle, which shape is depicted in Fig. 2. This cycle is defined by three parameters:

- Charge/discharge current I_{cycle} (equal to 100 A in Fig.2).
- Constant current time t_{plain}.
- Current ramp time t_{ramp}.

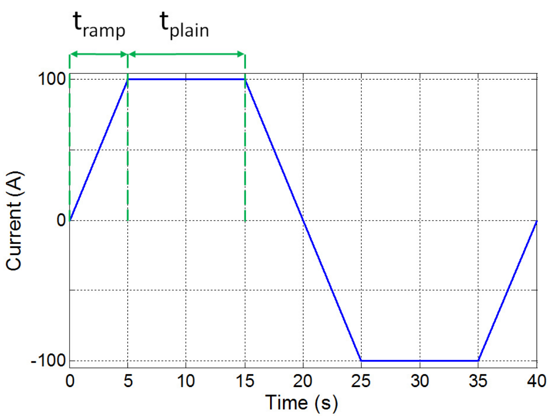

Figure 2: Symmetric charge/discharge cycle of 100 A.

So the cycle total time is:

$$t_F = 2 \cdot t_{plain} + 4 \cdot t_{ramp} \quad (1)$$

By testing the ESS with this symmetric cycle, the ESS is forced to give a certain amount of energy in the first half of the cycle. The same amount of energy will be absorbed in the second half. However, the ESS state of charge (SoC) at the end of the test will be slightly less than the initial SoC. The internal losses are responsible for this net discharge:

$$P_{losses} = R_{int} \cdot {I_{ESS}}^2 \quad (2)$$

In other words, due to the internal resistance (which models the vast majority of the internal losses within the ESS), the actual energy given to the ESS during the charging half (E_{charge}) is less than the energy drained from it during the discharging half ($E_{discharge}$).

Considering only the two constant-current parts of the cycle, one could calculate the internal resistance from the energy balance as follows:

$$R_{int} = \frac{P_{losses}}{{I_{ESS}}^2} = \frac{P_{losses}}{{I_{cycle}}^2} \quad (3)$$

where:

$$P_{losses} = \frac{\Delta energy}{time} = \frac{\int_{t=0}^{t_F} u_{ESS} \cdot i_{ESS} \cdot dt}{2 \cdot t_{plain}} \quad (4)$$

Equations (3) and (4) imply the following assumptions:

- All the losses are due to the internal resistance, considered as constant. In other words, self-discharge is assumed negligible. This is very reasonable, since the duration of the test is less than one minute.
- The internal resistance does not depend on the direction of the power flow (given a current and a temperature, the internal resistance is the same in charge and in discharge). This assumption means that an average charge-discharge internal resistance will be obtained, not being able to get the charging and discharging values separately with this test.
- The test is performed at constant temperature.
- t_{ramp} is much shorter than t_{plain}, making the consideration of constant current as almost exact.

The last consideration introduces an error in the calculation of the internal resistance, since some ramp will always exist regardless the testing equipment used. This error is inherent to the methodology; therefore it is called “intrinsic error”. The sign of this intrinsic error is always positive, meaning that the calculated R_{int} value will be higher than the actual value. This fact is illustrated in Fig.3, which shows the intrinsic error in percentage as a function of the t_{plain}/t_{ramp} ratio.

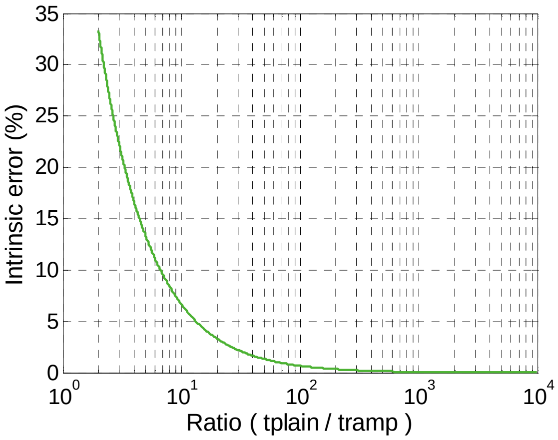

Figure 3: Intrinsic error (%) as a function of the t_{plain}/t_{ramp} ratio.

The intrinsic error may be easily minimized by increasing the t_{plain}/t_{ramp} ratio. As an example, the ratio used by the authors in the laboratory tests is:

$$\left.\begin{array}{r} t_{plain} = 14.92\ s \\ t_{ramp} = 0.04\ s \end{array}\right\} \Rightarrow ratio = 373 \qquad (5)$$

which implies an intrinsic error of 0.18%.

Besides all the aforementioned theoretical limitations, which are easily overcome, the method also has practical limitations. The most remarkable will be discussed next.

In order to perform the test, some testing equipment with current control capability is required. The instantaneous current set-point is given by the symmetric cycle. The method relies heavily on the current set-point tracking. All the deviations from the symmetric cycle reference will affect the calculated R_{int}. However, only those deviations which imply a net deviation will introduce some error in the determination of R_{int}. A bad set-point tracking leads to an error when the difference between both signals implies a net difference in the corresponding integral:

$$\begin{gathered} P_{losses,setpoint} = \frac{\int_{t=0}^{t_F} u_{ESS} \cdot i_{setpoint} \cdot dt}{2 \cdot t_{plain}} \\ P_{losses,actual} = \frac{\int_{t=0}^{t_F} u_{ESS} \cdot i_{actual} \cdot dt}{2 \cdot t_{plain}} \\ P_{losses,setpoint} < P_{losses,actual} \end{gathered} \qquad (6)$$

Improving the current set-point tracking is therefore very important in order to get an accurate value of R_{int}. Because of this, the current control regulation constants must be properly and finely adjusted. An example of this is shown in Fig.4. Besides, in this example the current error has both positive and negative sign, which further reduces the error in the calculation of R_{int} (given that an integral is involved).

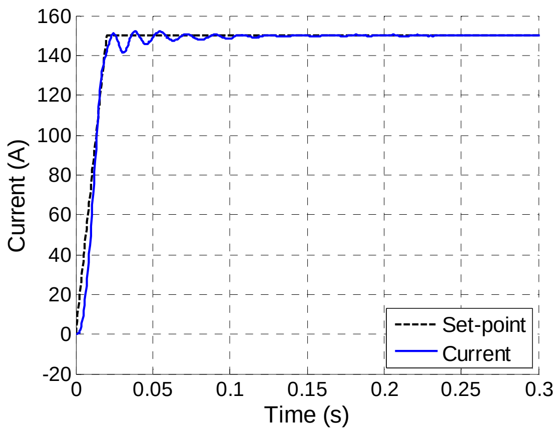

Figure 4: Current set-point and actual current during the first 0.3 seconds of a test with good regulators.

There is another obvious limitation of practical nature, also due to the difference between the current set-point and the actual current. This limitation is directly related to the current sensor accuracy. In this sense, the method is very sensitive to the offset of the current measurement. This fact is illustrated in Fig.5, which shows the lineal dependency between this so-called “offset error” and the current measurement offset.

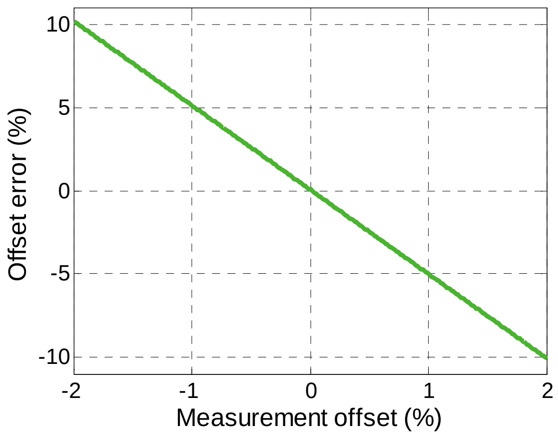

Figure 5: Offset error (%) as a function of the current measurement offset (%).

2.1.2 Self-discharge resistance test

The other parameter to be calculated, the self-discharge or parallel resistance (R_{self} in Fig.1), is less troublesome because of the following reasons:

- Self-discharge curves are usually provided by the manufacturer. This means that the data required to calculate R_{self} is available without the need to perform laboratory tests.
- Even if a test is to be carried out, it could not be simpler: It is enough to measure the ESS voltage once a day (or even once every two or three days). Naturally, the ESS must be in complete open-circuit conditions during the whole test.
- Anyhow, the accuracy in the calculation of R_{self} is not as critical as in the case of R_{int}. Relatively large deviations in the determination of R_{self} will have little consequences, given the long time needed for a conventional ESS to self-discharge (usually months). Since the dynamic behaviour of the ESS model will be practically the same, this parameter is less critical. It must be noted here, however, that R_{self} becomes more and more important as the system ages, so it cannot be neglected.

Once the voltage vs time data is obtained (either by tests or from the manufacturer), it must be converted to SoC vs time data. Depending on the ESS nature, this conversion may be very straightforward. For instance, ultracapacitors voltage and SoC are directly proportional. In other cases, such as batteries, a voltage vs SoC curve is required. This data is always provided by the manufacturer.

2.2 Considerations about flywheels and other ESS

So far, only batteries and ultracapacitors have been discussed in the paper, as they are the most mentioned technologies in the industry. However, the generality of the proposed model allows for a wider variety of ESS to be analysed and compared. Flywheels, of growing interest in large vehicles applications, are a good example of this.

Flywheels can be also studied with the proposed electric equivalent circuit. In this case, the capacitance is associated with the mechanical inertia and the current is equivalent to the speed. The series resistor is related to the electric losses at the electric machine and power electronics, while the parallel resistance models the mechanical losses (bearings and aerodynamic losses).

Similarly, a superconductor magnet energy storage (SMES) can be modelled with a similar circuit as well, by using a current source based circuit instead of a voltage source based circuit.

3 Laboratory tests with different ESS

This section is dedicated to the laboratory tests performed to calculate both R_{int} and R_{self} for several ESS: batteries (lead-acid and NiMH), ultracapacitors, and ultra-batteries (lithium-ion capacitors).

3.1 Test bench description

The power system of the test bench used during the tests is shown in Fig.6 [15]. It consists of the ESS under study (batteries, ultracapacitors, other devices, or combinations of two of them), a DC/DC power electronic converter, a DC/AC power electronic converter, and a tapped transformer connected to the 400 V grid. This topology allows the grid to exchange power with the ESS, whatever its voltage, while the inverter DC link voltage is kept constant.

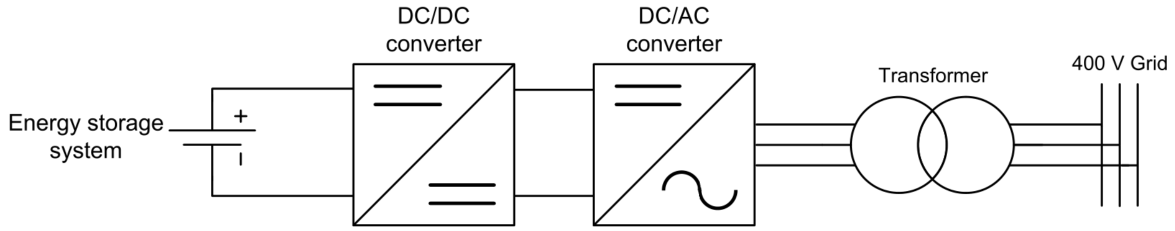

Figure 6: Test bench scheme.

The control hardware comprises electrical and thermal measurements, a digital signal processor (DSP) and a personal computer (PC).
The DC/DC converter is responsible for controlling the current in the ESS regardless its voltage. The control strategy is a PWM current control with a constant switching frequency of 5 kHz.
The DC/AC converter is controlled as a conventional inverter with reactive power control capability. This converter is responsible for controlling both the DC voltage in the DC link and the reactive power exchanged with the grid. The control strategy is a SVPWM current control with a constant switching frequency of 5 kHz.
In the assembled system, the rated voltage of the ESS must be comprised between 12 and 96 V. The rated power of the two electronic converters is 15 kVA, which allows charge/discharge currents up to 300 A [15].
All the energy storage systems are located inside a safety room, shown in Fig.7, with temperature control and fire suppression systems available.

3.2 Laboratory tests results

Four different ESS were tested in order to determine their electrical equivalent circuit: NiMH batteries, valve-regulated lead-acid (VRLA) batteries, double-layer ultracapacitors, and lithium-ion ultracapacitors (also called ultra-batteries). Tables 1 to 4 contain the main technical information regarding these four ESS.

Table1: NiMH batteries data.

Voltage	12 V / module	Current	200 A
Capacity	100 Ah (C/3)	Configuration	4 modules in series

Table2: VRLA batteries data.

Voltage	12 V / module	Current	200 / 25 A (discharge /charge)
Capacity	100 Ah (10h)	Configuration	4 modules in series

Table3: Ultracapacitors data.

Voltage	16 V / module	Current	600 A
Capacity	430 F	Configuration	5 modules in series

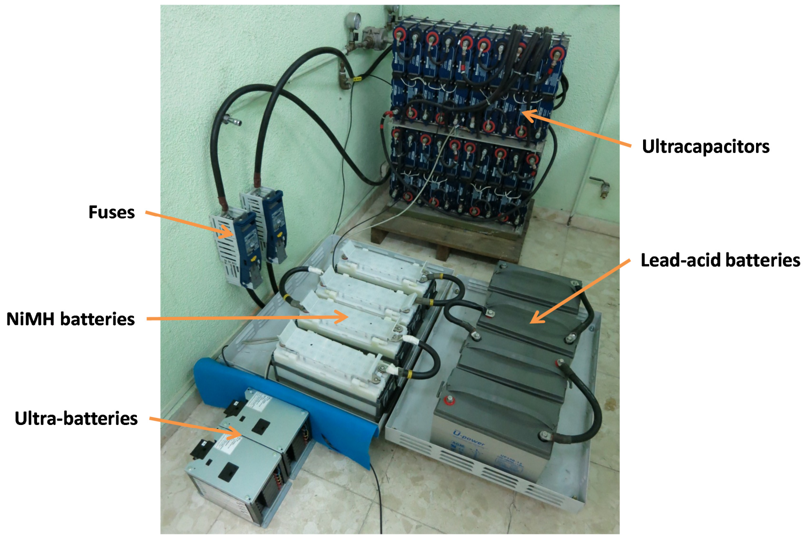

Figure 7: Safety room for batteries and ultracapacitors with different types of EES inside.

Table4: Ultra-batteries data.

Voltage	26-46 V /module	Current	100 A
Capacity	92 F	Configuration	1 single module

R_{int} was calculated for all four ESS following the methodology proposed in Section 2.1.1, using the parameters specified in (5) for a cycle total time of 30 seconds. Regarding I_{cycle}, different values were used (namely 25, 50, 75, 100, 125 and 150 A), so that the current dependency of the internal resistance could be analysed. The temperature of the ESS under study was properly monitored in order to keep it constant during the tests.
As an example, Fig.8 shows a NiMH test with I_{cycle} = 150 A and starting voltage around 52 V. The test lasts 30 seconds, and the current tracking is good enough to ensure that R_{int} is calculated with reasonable accuracy. The net voltage drop during the test is almost negligible, since the SoC of the battery barely decreases. But undoubtedly it does decrease, since there are always some losses.
Applying (4) to the data recorded during this specific test yields:

$$P_{losses} = \frac{\Delta energy}{time} = \frac{-23.7\ kJ}{29.84\ s} = -790\ W$$
$$R_{int} = \frac{P_{losses}}{I_{cycle}{}^2} = 35.2\ m\Omega \quad (7)$$

It is worth noticing that the average losses during this high-current test represent approximately 10% of the average power provided by the battery.
Tests results are depicted in Fig.9, which shows R_{int} as a function of the I_{cycle} current for the four ESS considered.
As expected, there is a wide difference between batteries and ultracapacitors regarding internal resistance. Both NiMH and VRLA batteries are above 45 mΩ, while the double-layer ultracapacitors barely reach 13 mΩ. The ultra-batteries (lithium ultracapacitors) behaviour is midway between both.
In general, the influence of the current over the internal resistance is small: no more than a 20% variation in relative terms, with the exception of the ultra-batteries. With very low currents the method becomes less accurate, so no results are obtained below 25 A.

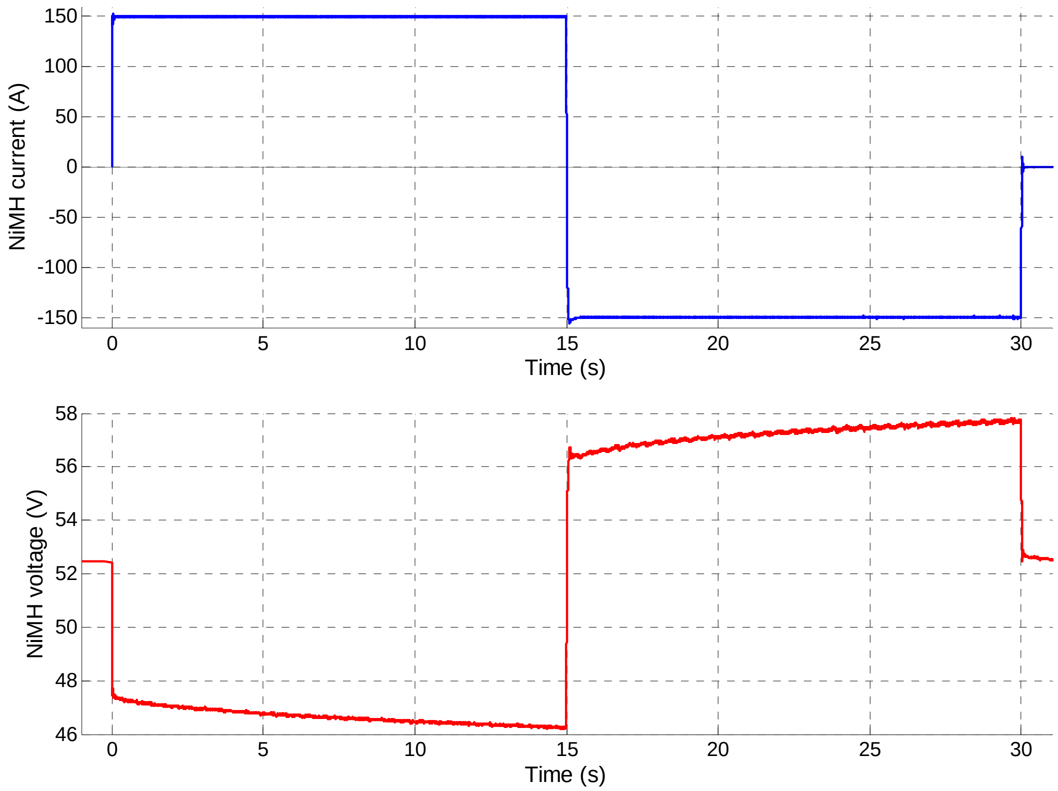

Figure 8: NiMH internal resistance test.

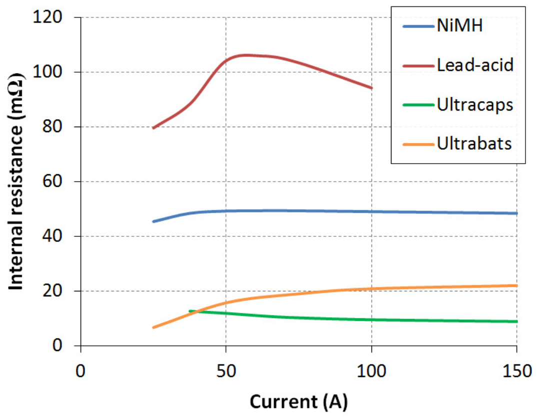

Figure 9: Internal resistance as a function of the I_{cycle} current.

So far, only constant-temperature tests have been presented. However, the proposed method may be used to study the influence of the temperature over the internal resistance as well.

To do so, several identical tests are performed consecutively, I_{cycle} having the same value in all of them. The temperature of the ESS increases during this succession of tests as a consequence of its internal losses. To further improve the heating, an adiabatic envelop is used, so that the heat transfer between the ESS and the air is severely reduced. This way, the heat is not delivered to the surrounding air and it is mainly used to increase the temperature of the device.

Each test lasts 30 seconds, and 10 seconds of pause separate one test from the next. Hundreds of tests (namely between 400 and 500) are automatically carried out in a row during a few hours. The exact time needed to produce a certain temperature rise varies greatly from one ESS to another. Three reasons justify this behaviour:

- The thermal properties of the ESS under consideration (given by their materials, sizes, surfaces, even colours) are very different.
- Different current values were used for each ESS because of their own current limitations. Lead-acid batteries are the most restrictive in this sense (75 A), while the ultracapacitors allow for more than twice that value (150 A were used).
- Even if the same current was used for all the ESS, the losses within each one of them would not be the same. This is due to their different internal resistance values, already shown in Fig.9.

Tests results are depicted in Fig.10, which clearly illustrates the deep differences between the various ESS. While both batteries have a strong temperature dependency, the ultra-capacitors seem to be quite insensitive to heating, at least in the temperature range considered. Once again, the ultra-batteries have an intermediate behaviour.

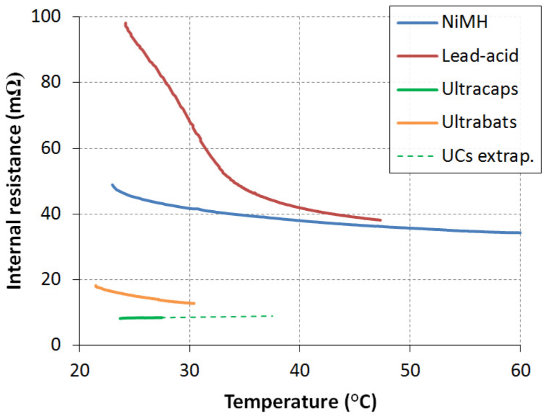

Figure 10: Internal resistance as a function of the temperature.

One of the most difficult aspects of these tests is how to correctly consider the internal temperature of the ESS under study, given that no temperature sensors are placed inside them. External sensors are only capable of giving information about how the heat is evacuated, but this is about the thermal design of the device case and not about its actual thermal status. Besides, the heating inside the ESS is far from being heterogeneous, which makes the estimation of the internal temperature even harder.

Therefore, there is a considerable time-delay between a given measurement and the actual internal temperature of the system, which must be somehow compensated. However, this time-delay only affects the x-axis position of the curves in Fig.10, but not their shape. This means that even with bad time-delay compensation, the dependencies of the internal resistances with the temperature are the ones showed in Fig.10.

Regarding the self-discharge of the different ESS taken into account, tests results are shown in Fig.11. As expected, the ultracapacitors lose voltage faster than the rest of ESS. The VRLA battery voltage also drops quite steeply. However, due to the non-linear relationship between voltage and SoC in VRLA batteries (the voltage decreases very sharply at the beginning of the discharge curve), this result is not unexpected.

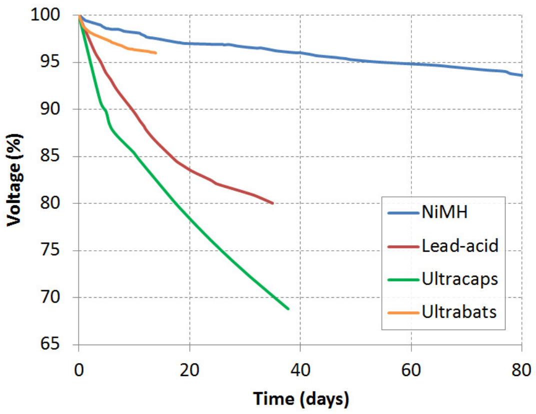

Figure 11: Self-discharge for all the ESS under consideration.

Anyhow, all the ESS under study have a slow discharge rate when compared to any other load that may be connected to them, even if that load is very small (such as a voltage sensor).

4 ESS comparison

When a manufacturer has to choose a proper ESS for an EV, three main aspects must be taken into account: technical parameters (stored energy, losses/efficiency, heating, self-discharge, energy and power density), useful life and maintenance, and cost. In this work, only the first and the last one are considered, since deep-cycle testing is beyond the scope of this paper.

Table 5 summarizes the results obtained for the four ESS studied in this paper. It must be noted here that these results do not consider a single module of each ESS, but a combination of modules so that the resulting system has a voltage around 50 V.

From Table 5, it is clear that the NiMH batteries are way superior to the VRLA batteries in terms of efficiency, heating and self-discharge. Regarding the ultracapacitors, the conventional double-layer technology has proven more successful than the novel lithium ultracapacitors, which suffer from worse performance and less robustness, although their capability to store energy is higher.

Besides the strictly technical comparison, other practical considerations must be taken into account in order to provide more information, so that the most appropriate technology for a certain EV application may be identified. This analysis should include power and energy density (in terms of both mass and volume), as well as price. Table 5 also shows this comparison of energy density, power density and cost for each ESS.

The ultracapacitors show the higher power density but the lower energy density, just the opposite than the batteries, while the ultra-batteries present an intermediate behavior between both. Considering only the different type of batteries which has been dealt with, the NiMH batteries show higher performance as compared with the VRLA batteries, but the price of the former is twice the price of the latter.

Besides the higher power and energy density of the NiMH batteries, it should also be noted that the VRLA batteries do not allow the same maximum current when charging than that obtained during the discharge. This last limitation is very important concerning the application, since in EVs and HVs it is usual to deal with aggressive decelerations. The high currents achieved during these decelerations must be absorbed by the ESS in order to maintain a high regenerative breaking level, which is essential to the global vehicle efficiency.

Lithium batteries are the more widely spread solution concerning EVs. However, results have not been included in this study yet; they will be carried out in the next stage. Lithium batteries have higher power and energy density as compared with the NiMH batteries, while keeping a similar price. There are different technologies (Co, Fe,

Table5: ESS comparison.

	Rint		Self-discharge		Energy	Power	Density	Cost	
	mΩ	Qualitat.	SoC/day	Qualitat.	Wh/kg	W/kg	kg/m^3	€/kWh	€/kW
NiMH (4 mod.)	50	Average	-0.1%	Very good	66	150	2038	1836	808
VRLA (4 mod.)	90	Bad	-0.3%	Good	40	80	2389	205	102
UCs (5 mod.)	10	Very good	-0.6%	Medium	5.6	10400	1063	17856	9.6
UBs (1 mod.)	18	Good	-0.2%	Good	10	1400	727	47200	337

Mn, air, etc.) which allow for a great expectation in a near future around this type of chemistry.

5 Conclusions

From the point of view of the EV manufacturer, it is not always easy to decide what the most appropriate ESS is for a given EV. There are many accurate and very complex models for batteries and other ESS that attempt to help in this choice. However, their lack of generality makes it very hard to compare between different technologies. In this paper, a different approach is proposed. Instead of using a very accurate but very specific model for each ESS, a bunch of simple and straightforward laboratory tests is proposed to obtain a general and simple electric model. This way, several devices can be compared qualitatively, thus getting practical information useful to select the most suitable ESS.

The proposed methodology has been applied to four different ESS of similar voltage and capacity but different technologies (NiMH batteries, VRLA batteries, ultracapacitors and lithium capacitors). Internal resistance and self-discharge have been determined by means of laboratory tests. Energy density, power density and cost have also been taken into account in the comparison, resulting that NiMH and the double-layer ultracapacitors are the best solutions in this case.

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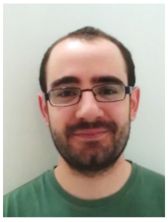

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