Inexpensive experimental design to learn energetic parameters of supercapacitors

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Abstract. In this paper is presented an inexpensive experimental design to learn energetic parameters of supercapacitor, in which is used an embedded system (Arduino Yun). This design is defined in order to help engineering students to learn and understand energetics parameters of electrochemical double-layer capacitors. Besides, the design is based on flexible and open-source software and hardware, this is an important features, because the students must be capable to modify this experimental design. It has implemented a series of tests based on European standards defined for supercapacitors (IEC 62391−1, IEC 62391−2−1, IEC 62391 − 2, IEC 62576). It is exposed obtained results, with the experimental design, with some commercial supercapacitors, from tests carried out, as defined in the standards. These results demonstrate that the experimental design is feasible for learning and obtaining energy parameters of supercapacitors.

Keywords

Electrochemical double-layer capacitor, Learning artifact, Electrical energy storing, Embedded Systems, Inexpensive experimental design

1. Introduction

Over the last years, it has increased a significant development in electrical storage systems with supercapacitors, also known as electrochemical double layer capacitors (EDLC). These systems are elements capable of storing electrical energy, with nonlinear behaviour [1, 2]. As a result of the importance that have obtained these devices, it has been developed a series of European standards. These standards set specifications and ways to define them. Among these standards could include: **Fixed electric double-layer capacitors for use in electronic equipment** (Part 1 : Generic specification) IEC 62391 − 1, **Fixed electric double-layer capacitors for use in electronic equipment** (Part 2-1 : Blank detail specification - Electric double-layer capacitor for power applications - Assessment level EZ) IEC 62391−2−1, **Fixed electric double-layer capacitors for use in electronic equipmen**t (Part 2 : Sectional specification - Electric double-layer capacitor for power applications) IEC 62391 − 2, **Electric double-layer capacitors for uses in hybrid electric vehicles** - Test methods for electrical characteristics IEC 62576. The characteristics of the EDLCs are complementary with current battery systems, so can be achieved mixed configurations (supercapacitors and batteries) that allow designing systems for storing and retrieving electric power, with an improved dynamic and performance [3–5].

As consequence of the importance that the EDLCs are having in the field of electrical energy storage systems, it is possible to indicate that would be interesting that may be studied at engineering degrees. For that, it would be necessary to design learning strategies, which help students to learn and understand the energetic parameters related to EDLCs, as well as their behavior in different situations, with respect to electrical energy storage systems. Learning strategies could be based on the use of artefacts or experimental designs, at laboratory, designed for the study and analysis of EDLCs. This last educational proposal is based on psychological learning theories exposed in several papers [6–9], whiches refer that students can reinforce their learning through appropriate learning environments, and besides through using, constructing and designing artifacts. In the case of EDLCs, the artifacts can reproduce real operating situations , such as those set out in the **European standards for EDLCs**, in this way is achieving an adequate experimental environment in line with constructive approach to learn through action [6, 10]. These artifacts can be planned in prototype form, in which is possible to use low cost embedded systems, allowing considerable flexibility in the design of experiments, as reflected in the large number of papers published in this line [7, 8, 11–13].

The main objetive of this paper is to show an inexpensive experimental design, to help engineering students learn and understand energetic parameters of electrochemical double-layer capacitors. The mentioned parameters are some of the established at the **European standards** (IEC 62391 − 1 // IEC 62391 − 2 − 1 // IEC 62576), being the experimental design based on the use of a low cost embedded system.

2. Materials and methods

To validate the viability of the proposed experimental design, experimental data are required, so there have been carried out a series of laboratory tests to obtain them, based on established methods by **European standards** for EDLCs. In this section, materials and methods used are displayed, for this purpose.

A. Materials

In fig.1, a basic diagram of the experimental design is displayed. This equipment consists of the following elements:

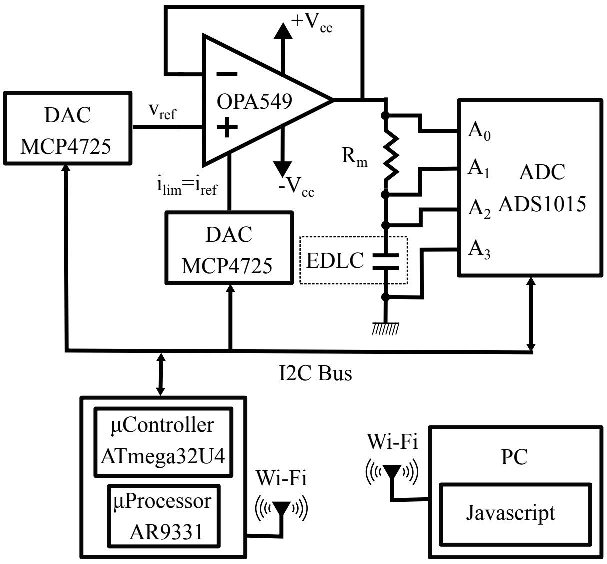

Figure 1: Basic diagram of the experimental design.

1. A power operational amplifier **OPA549** *(Texas Instruments)*, fig. 2. This operational amplifier can provide a nominal current of $8A$, and also has a special input (i_{lim}) for limiting the output current of the amplifier. This is an important feature for implementing galvanostatic charge or discharge (by controlling the current).

Figure 2: Power operational amplifier **OPA549**.

2. An analogical-digital convertion stage, fig. 3, based on the precision converter **ADS1115** *(Texas Instruments)*, which is mounted in a breakboard of *Adafruit Industries*. This stage has two differential analog inputs for measuring: the charging or discharging current and the voltage of EDLC. Current $i(t)$ is measured from the voltage of a resistor $R_m = 0.1\Omega$ which is arranged between the output of the operational amplifier and capacitor, and the EDLC voltage $v(t)$ directly. The circuit **ADS1115** has a $16Bit$ resolution, which sets a resolution of $3mV$ for the voltage measuring and $30mA$ for the current measuring.

3. Two digital-analogical convertion stage, fig. 4, based on **MCP4725** (MICROCHIP) with a resolution of $12Bit$, which are mounted in a breakboard of *Adafruit Industries*. These stages are used to control the charging-discharging processes of EDLC, for setting the voltage and current intensity references.

Figure 3: Analogical-digital converter **ADS1115**.

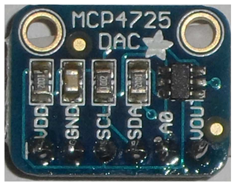

Figure 4: Digital-analogical converter **MCP4725**.

4. A microcontroller **ATmega32U4** model *(Atmel)* and a microprocessor **AR9331 (Lilino - Linux environment)**, implemented in an ***Embedded system***, which is called **Arduino Yun** *(Arduino)*, fig 5. This microcontroller is responsible for directly controlling the galvanostatic charging process, so as to capture the data and send them, **via WiFi**, to a PC for saving them.

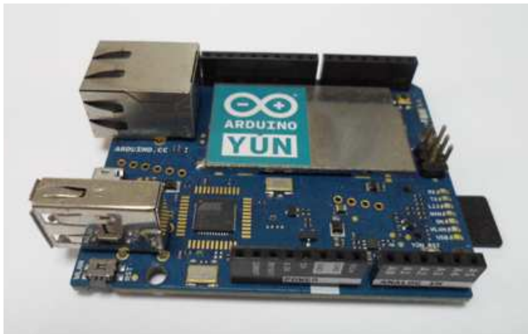

Figure 5: Arduino Yun.

5. A PC, that is responsible for controlling and configuring the microcontroller for conducting the tests and storage of data, obtained from the measurements. This is achieved through a script made in javascript languaje under **Processing** *Processing Foundation*. The script is an interface to comunicate and control the embedded system (Arduino Yun) with the PC. Processing is a flexible and open-source software sketchbook, fig 6. It runs on Windows, Mac OS X, and Linux. There is much information available on the internet, for programming in this platform.

Finally, fig. 7 displays a picture of the system.

Figure 6: Processing IDE.

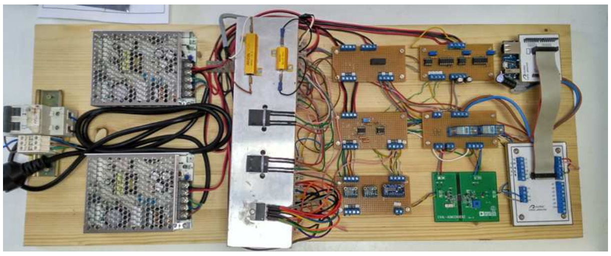

Figure 7: Picture of the experimental design.

B. *Tests and measurement procedures*

In the standards listed above (IEC $62391-1$ // IEC $62391-2-1$ // IEC 62576), different types of tests for determining the properties of supercapacitors are shown. These tests can be classified into the following

- For obtaining the capacitance C:
  - Constant current discharge methods.
  - Constant resistance charging methods.
- For determining the internal resistance R_N:
  - AC resistance methods.
  - DC resistance methods.
- For estimating the leakage current.
- For analizing Self-discharge.
- For obtaining the energy efficiency.
- etc...

The experimental design proposed in this paper, although it could implement the commented tests, it has been only shown results of operations of two of them, to demonstrate proper operation, as specified in the standards . Then, it goes to briefly describe the tests used in this article for the determination of: the capacitance by the method of discharge at constant current; and the test for obtaining energy efficiency.

Capacitance: for determining the capacitance is planned to use the constant current discharge method. For the application of this method, it will establish the charge-discharge profile displayed by fig. 8, in which initially is realized a galvanostatic charging process till the rated-voltage U_R, then in galvanostatic form, the supercapacitor is charged during $30min$, and finally a galvanostatic discharge is realized, with a discharging current determined as set out at discharge conditions, at table 2 of the European Standard IEC $62391-1$. Capacitance is determined from expression (1), where U_1 and U_2 are the eighty and forty percent of the rated-voltage U_R, so $U_1 = 0.8 \cdot U_R$ and $U_2 = 0.4 \cdot U_R$.

$$C = \frac{U_1 - U_2}{I(t_2 - t_1)} \quad (1)$$

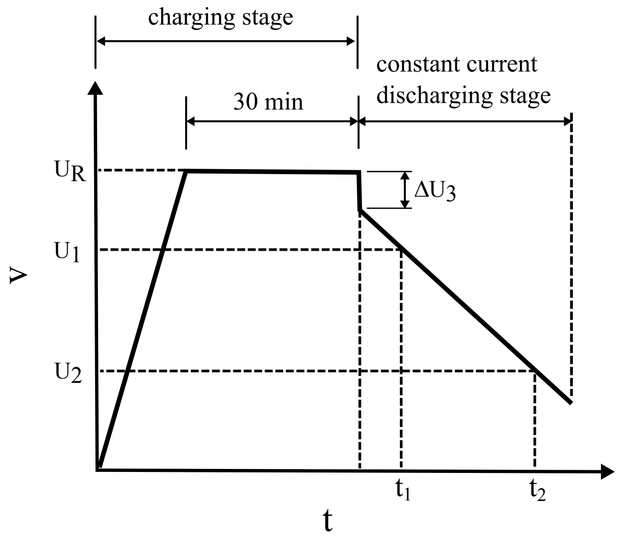

Figure 8: Constant current discharging procedure to determinate the Capacitance.

Energy Efficiency: for the determination of energy efficiency of the supercapacitor, it will be applied the established method at section **4.3. Energy efficiency** of the European Standard IEC 62576. Figure 9 displays the operation profile, established by the cited standard.

In this method, for the determination of the energy efficiency, it is considered five stage:

1. Starting from the fully discharged supercapacitor, it is realized a galvanostatic charge till the half rated-voltage $0.5 \cdot U_R$, whose load current is determined by expression (2),

$$I_C = \frac{U_R}{40 \cdot R_N} \quad (2)$$

being R_N the rated internal resistance.

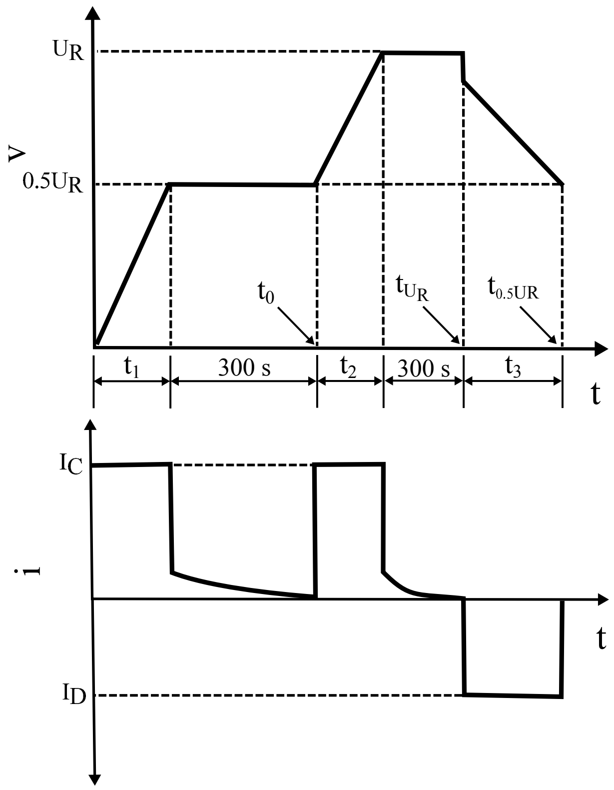

Figure 9: Charging-discharging profile to determinate the energy efficiency.

2. Then, it is performed a potentiostatic charge during $300s$.
3. In the next stage, it is performed a new galvanostatic charge, with the same value of the current (2), till the rated-voltage.
4. After this last galvanostatic charge, it will proceed to another pontentiostatic charge, to the rated-voltaged, during $300s$.
5. In the last stage, it will realize a galvanostatic discharge till the half rated-voltage, with a discharge current determined by the expression (3).

$$I_D = \frac{U_R}{38 \cdot R_N} \tag{3}$$

being R_N the rated internal resistance.

From data, obtained of the established test, it is possible determine the energy efficiency by means of the expressions (4), (5) and (6).

$$E_f(\%) = \frac{W_D}{W_C} \cdot 100 \tag{4}$$

$$W_D = \int_{t_{U_R}}^{t_{0.5U_R}} I_D U(t) dt \tag{5}$$

$$W_C = \int_{t_0}^{t_{U_R}} I_C U(t) dt \tag{6}$$

The proposed tests have been programmed in an embedded system (Arduino Yun), by utilizing of the Arduino IDE, at fig 10 is displayed a screen of this application. The open-source Arduino Software (IDE) is used to write code and upload it to the board (Arduino Yun). It runs on Windows, Mac OS X, and Linux. There is much information available on the internet, for programming in this platform. Also, it turns out to be an easy to use platform by anyone, without the need of extensive knowledge of programming of embedded systems. These stated features, make that the embedded system used has a great flexibility when developing projects similar to the proposed in this paper.

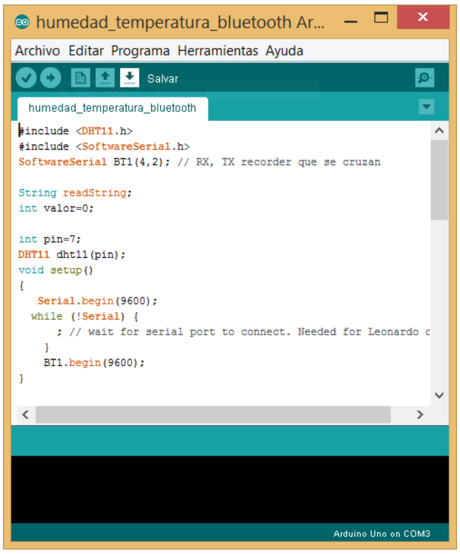

Figure 10: Arduino IDE.

3. Results

It has made a series of tests based on European Standards, for a set of supercapacitors from different manufacturers and models, whose basic features are shown in the table 1, as well as pictures of them in figures 11 and 12.

For handling the data obtained, in the tests performed with the experimental design, it has been used calculation tool **Scilab**. Scilab is an open source, cross-platform numerical computational package and a high-level, numerically oriented programming language.

Figure 11: Picture of the experimental design.

Table 1: EDLCs used in this paper.

EDLC	Manufacturer	Tradename	Rated-capacitance (F)	Rated-voltage (V)
1	Epcos	Ultracap	5	2.3
3	Wima	Supercap R	100	2.5
5	Maxwell	BCAP0650	650	2.7

Figure 12: Picture of the experimental design.

Figures 13 and 14 display two constant current discharging tests, for the first and third EDLCs of the table 1. With data obtained from these test is possible to determinate the capacitance, of two EDLCs, by means of the expression (1). For the first EDLC is determined following (7):

$$C = \frac{I(t_2 - t_1)}{U_1 - U_2} = \frac{0.61 \cdot (2020.5 - 2012)}{0.8 \cdot 2.3 - 0.4 \cdot 2.3} = 5.63F \tag{7}$$

The capacitance value is obtained by (7), which is inside the tolerance value established by the manufacturer $-10\%//30\%$.

For the third EDLC (8)

$$C = \frac{I(t_2 - t_1)}{U_1 - U_2} = \frac{0.7 \cdot (6570 - 5490)}{0.8 \cdot 2.7 - 0.4 \cdot 2.7} = 700F \tag{8}$$

The capacitance value is obtained by (8), which is inside the tolerance value established by the manufacturer $-10\%//10\%$.

Figure 15 displays a energy efficency test, for the second EDLC of the table 1. For this test, the discharged energy has a value of $W_D = 172J$, with a discharging current of $I_D = U_R/40R_N = 2.5/40 \cdot 0.096 = 0.651A$ (where the rated internal resistance R_N has been determined experimentally using the fixed method at the annex D of the European Standard IEC 62576), and the charged energy, with a charging current of $I_C = U_R/38R_N = 2.5/38 \cdot 0.096 = 0.683A$ (where the rated internal resistance R_N has been determined experimentally using the fixed method at the annex D of the European Standard IEC 62576) $W_C = 249.4J$, determined by the expressions (5) and (6). Finally , applying the expression (4), it is possible to obtain the energy efficiency of the test $E_f = 73.5\%$.

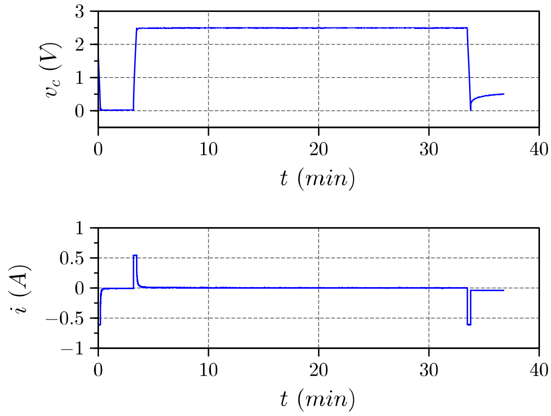

Figure 13: Constant current discharging method, for estimating the capacitance. Epcos $5F$ Ultracap supercapacitor.

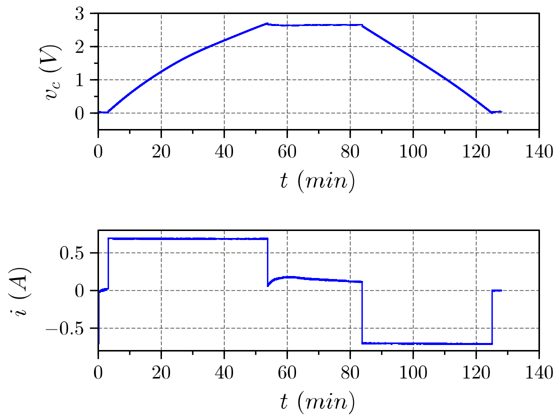

Figure 14: Constant current discharging method, for estimating the capacitance. Maxwell $650F$ BCAP0650 supercapacitor.

4. Conclusions

In this paper is presented an inexpensive experimental design to learn energetic parameters of supercapacitor, in which is used an embedded system (Arduino Yun). This design is defined in order to help engineering students to learn and understand energetics parameters of electrochemical double-layer capacitors. Besides, the design is based on flexible and open-source software and hardware, this is an important features, because the students must be capable to modify this experimental design. It has implemented a series of tests based on European standards defined for supercapacitors (IEC $62391-1$, IEC $62391-2-1$, IEC $62391-2$, IEC 62576). It is exposed obtained results, with the experimental design, with some commer-

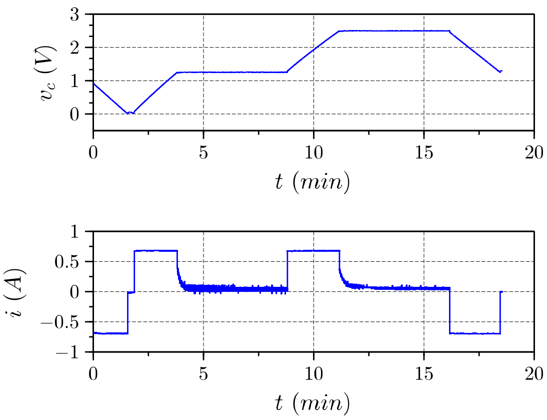

Figure 15: Energy efficiency method. Wima $100F$ Supercap R supercapacitor.

cial supercapacitors, from tests carried out, as defined in the standards. These results demonstrate that the experimental design is feasible for learning and obtaining energy parameters of supercapacitors. Finally, is possible to indicate that the proposed experimental design has a low cost, because the different elements are inexpensive and have very high flexibility in their design, both hardware and software dimensions.

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