Dynamic Model Battery Emulator and Power Profiler for IoT Devices

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Abstract— In today's technology-driven society, batteries power many applications and devices, from low-power electronic devices to high-power devices. Batteries store electrical energy in the form of chemical energy in a safe and portable way. There are different types of batteries, each with its own specifications. However, the most common batteries are alkaline and lithium batteries. Today's focus is on IoT technologies and the existence of batteries allows the connection of mobile or autonomous nodes. Therefore, as IoT equipment is constantly expanding, the number of batteries produced is also constantly expanding. This isn't a positive point, because although the communication protocols developed consider the consumption of the batteries, the increase of energy production is greater and sometimes there is an uncontrollable disposal of batteries. Since most devices may be in difficult to reach locations, it is intended that the batteries be capable of storing energy for years without having to make a switch. In addition, IoT tests require exchanges and tests on different batteries which are then discarded without even having full use because they don't fit the intended application. For this reason, the use of a battery simulator is a great advantage because it allows to increase the battery saving and sometimes it reduces unnecessary energy expenses.

This project includes a brief explanation about the operation of a common battery, about its chemistry, the constitution of an alkaline battery, a lithium battery and the difference between the two. The charge status (SOC) subject will be addressed generally and focused on alkaline and lithium batteries, along with effects that affect the state of charge of a battery. In addition, a brief explanation will be taken to the state of health of a battery, the main points that are needed to model a battery and finally a study is made to existing systems to simulate batteries (battery simulators).

In the battery emulator part, a list of required requirements is made for the system, the system architecture is presented with hardware, software and firmware, and finally, the results and project specifications will be presented. This section will contain tests about voltage control, resistance measurement and current measurement.

Keywords—battery, alkaline, lithium, charge, voltage, IoT, SoC, state of health, battery emulator, resistance

I. INTRODUCTION

The objective of this work is to develop custom power supply equipment that can emulate a certain behavior of a battery over its lifetime. The equipment will be developed in terms of charge availability, open cell voltage and output resistance and will allow to evaluate the proper operation and power consumption of devices with different battery models and conditions.

Nowadays objects have the ability to communicate to be connected to the Internet. Devices can be accessed and controlled remotely, creating a worldwide opportunity for innovation. Each electronic device can be identified on a network, making it quick and simple to connect different devices. This is what is called the Internet of Things (IoT). The IoT concept is the sharing of data and information using technologically evolving devices and systems over normally wireless networks - Wireless Sensor Networks (WSNs) [1]. Wireless sensor networks are connected sensor nodes that collect data about the physical condition of an environment [1]. There are several wireless technologies in IoT, such as Bluetooth, WirelessHART, Sigfox, Wifi, NFC, LoraWAN, among others. In addition, IoT includes the full adoption of internet usage coupled with the use of semiconductor components and reduced size sensor technologies. The main components of IoT are IoT devices, the network, application platforms and IoT applications [1]. However, none of this is possible if there were no batteries. Due to increasing technological, advances in electrochemistry and manufacturing techniques, there are now different types of batteries, each with their own specifications.

A battery is made up of several electrochemical cells and transforms chemical energy into electrical energy through an oxidation-reduction reaction that occurs inside the battery. The chemical reaction that occurs inside a battery has a certain speed, which corresponds to the transfer rate of electrons, which in turn controls the amount of electrons that flow between the two terminals. Electrodes are the current conductors of the battery, and electrolyte is the aqueous solution that acts on the electrodes. The batteries are characterized by their state of charge (SOC) which indicates how much the battery has already been used and is used to know the remaining capacity of the battery, which is very important for the management of the battery. The state of charge can be calculated by several methods and can be affected by several parameters, such as temperature, which is the parameter that most influences the SOC.

Simulators are electronic devices capable of replacing a real battery. Sometimes it is necessary to use to many batteries to test various equipment and devices, which leads to a waste of batteries. With the simulators this no longer happens, because with the simulator it is possible to simulate all the batteries that would be necessary, without having a waste of real batteries. It is important to reduce device consumption due to economic reasons, avoiding battery replacement and recharging, operational reasons if it is impossible to change or recharge, and eco-friendly reasons, reducing the number of times that we change a battery or replace a disposable device. The simulators are very important because with its use, it reduces the testing time, provides repeatable test results, improve safety and has a digital visualization of the results. This reduces the number of actual tests leading to an ecological benefit.

This project proposes to formulate a generic model of a power supply equipment capable of emulating a certain behavior of a battery over time. This model is intended for disposable and rechargeable alkaline and lithium batteries. A power supply architecture will be defined, and the system will be controlled from a Python user interface to run on a personal computer.

II. STATE OF THE ART

A. *Battery Chemistry*

A battery is a device composed of one or more electrochemical cells in series or parallel. An electrochemical cell consists of a generally separate set of electrodes, electrolytes, and terminals. An electrode is a conductive part that is in electrical contact with a low conductivity medium and can emit or receive charge carriers. These electrodes consist of the anode - electrode that emits positively charged carriers and receives negative charge carriers from the low conductivity medium - and the cathode - electrode that emits electrons and can receive positive charge carriers. Electrolyte is a liquid or solid substance consisting of ions that move, making it ionically conductive. It is also the separator between anode and cathode, preventing physical contact between the electrodes [2].

The purpose of a battery is to convert chemical energy into electrical energy from an electrochemical reaction, which involves oxidation and reduction of electron-transferring chemicals to an active material. This reaction is called an oxidation – reduction reaction or redox reaction.

Oxidation occurs when there is the transfer of electrons that are emitted by the cathode [4] as in

$$M \rightarrow M^{+n} + ne^{-} \quad (1)$$

Reduction occurs when oxygen is removed from an oxide and an ionic substance gains electrons as in

$$M^{+n} + e^{-} \rightarrow M^{+(n-1)} \quad (2)$$

Batteries suffer from a discharge process and a charging process. The first happens spontaneously and consists of an operation in which the battery supplies electrical energy produced in cells to an external circuit under specified conditions [2]. In the charging process the battery will receive electricity. During discharge, the anode is the negative electrode and the cathode is the positive electrode. These processes can be observed in Figure 1.

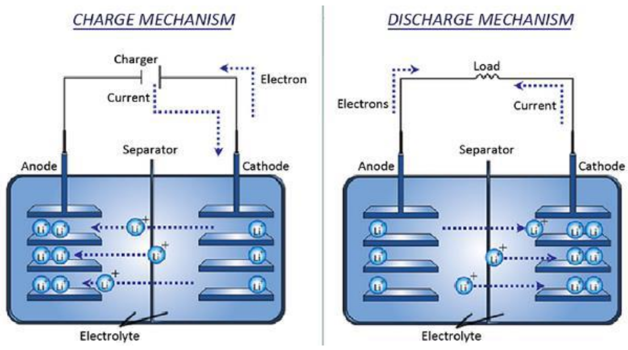

Figure 1. Process of charge and discharge of a battery [3].

Batteries can be classified as primary or secondary. A primary battery is a battery that is not designed to be recharged electrically, while a secondary battery is designed to be recharged. Recharging is performed by the oxidation-reduction reaction [2].

B. *Alkaline Batteries*

An alkaline battery contains an alkaline electrolyte and can be primary (non-rechargeable) or secondary (rechargeable) [2]. The alkaline batteries are composed of an alkaline electrolyte of potassium hydroxide an in these batteries the anode is zinc and the cathode is magnesium dioxide. At the discharge, only zinc and magnesium dioxide are consumed, not affecting the electrolyte. The redox reaction is given by

$$Zn_{(s)} + 2MnO_{2(s)} \rightleftarrows ZnO_{(s)} + Mn_2O_3(s) \quad (3)$$

The electrolyte mixture is composed of sodium hydroxide or potassium hydroxide, because it makes the electric charge transfer easier. Because of this, it stores more power for a longer life than a standard battery. Its capacity is good because the magnesium dioxide is pure and dense, but nevertheless, it is quite dependent on the charge. The battery voltage decreases steadily during its use and therefore the total capacity that is used depends on the supply voltage range and the application.

Defined by manufacturers' standards, the nominal voltage of a new alkaline battery is 1.5 V. The amount of current it can deliver is usually proportional to its physical size as the internal resistance decreases as the inner surface of the cell increases. These batteries have a high density and a long life with the same voltage.

C. *Lithium Batteries*

A lithium battery is made up of several lithium cells that contain a non-aqueous electrolyte and a lithium negative electrode and can be classified into primary or secondary batteries such as alkaline batteries. [2].

Most Li-ion batteries are identical because they are composed of a metal oxide (cathode) coated by an aluminum current collector, carbon or graphite (anode) coated by a copper current collector and an electrolyte made of lithium salt in an organic solvent. They don’t need to be kept in a constant state of tension for long periods of time. When they reach maximum voltage, it no longer needs to be charged and during discharge they maintain a much higher voltage than other types of batteries. This type of batteries has several advantages, because they have high specific energy and great load capacity, low internal resistance, short charge times and low self-discharge, long life cycle, no maintenance required, don’t release dangerous gases.

However, they have some limitations because they need a protection circuit to prevent thermal leakage; degrades at very high temperatures and when storing very high voltages; in low temperatures don’t load quickly and transport regulations are required for shipments of many quantities of this type of battery.

There are about six lithium battery chemistries: cobalt lithium oxide (LCO - LiCoO2), lithium manganese oxide (LMO - LiMn204), cobalt niguel manganese lithium oxide (NMC - LiNiMnCoO2), lithium iron phosphate (LFP - LiFePO4), lithium nickel cobalt aluminum (NCA - LiNiCoAIO2) and lithium titanate (LTO - Li4Ti5O12).

D. State of Charge

The state of charge of a battery is the indicator of the amount of usable battery remaining and is given by

$$SOC(t) = \frac{Q(t)}{Q_n} \tag{4}$$

SOC is the quotient between the payload amount and the usable capacity of the battery. The payload corresponds to the charge the battery has from one moment to its full discharge state, and the payload capacity is the maximum charge that a battery can deliver in its full charge state. Since the payload amount is always less than the payload capacity, the decimal charge state values are always greater than or equal to zero and less than or equal to one and are expressed as a percentage.

In addition to the state of charge there is a depth of discharge (DOD) which is the inverse of the charge state because it indicates the amount of battery that has already been used. To determine the capacity of the battery you can use the discharged time.

Charging status is important for extending battery life and for remaining battery capacity. However, SOC is a nonlinear function that depends on several parameters, such as temperature, charge/discharge rate, hysteresis, auto discharge and cell age.

To measure the state of charge there is no direct or exact way, but several methods can be used to estimate its value with some precision. The measurement method used to determine the SoC of a battery should be simple, convenient, practical and reliable. The methods of load measurement can be direct or indirect, and the use of adaptive systems can still be used. The adaptive systems are applied on the battery measurements and allow a better estimation of the state of charge. The direct methods consist of measuring the variables of a battery, that is, measuring voltage, impedance and voltage relaxation time (T) when a current is applied. The indirect methods are based on coulometric systems, which determine the amount of matter transformed during an electrolysis reaction, by measuring the amount of electricity that is consumed or produced. The charging or discharging current of a battery is measured. By applying these methods, it is possible to measure the voltage and temperature, resulting in a more accurate system than using a direct method. About adaptive systems, the Kalman filter, fuzzy logic, neural network, and others are used.

In lithium batteries it is not very simple to determine the state of charge as the capacity the cell uses is not constant as it varies with the temperature, discharge rates and age of the cell. These batteries have the disadvantage that they are difficult to fully recharge for good cycle and life. Figure 2 shows a SOC analysis of a lithium battery.

The most common method for determining the SOC of alkaline batteries is to measure open circuit voltage and calculate output resistance.

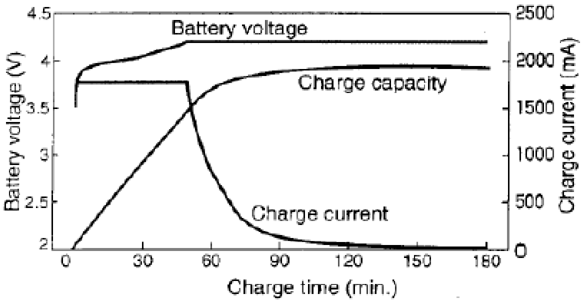

Figure 2. Lithium-ion battery at 20ºC [8].

As charging time increases, charging current decreases and charging capacity increases. Until approximately 60 minutes, the charge current remains constant, along with the linear increase in charge capacity and the linear increase in battery voltage. After 60 minutes occurs an exponential decrease in the charging current, keeping the charge capacity and the battery voltage practically constant.

The internal resistance of alkaline batteries varies as it is discharged. Alkaline batteries typically have an inclined discharge curve, and most devices that use alkaline batteries are designed to operate within a voltage range of 0.9 V to 1.6 V to participate in this discharge characteristic.

Temperature affects battery performance and capacity. Cold temperatures cause electrochemical reactions to slow down and reduce ion mobility, which causes an increase in the internal resistance of the battery as the temperature decreases. The internal resistance of alkaline batteries decreases significantly with increasing temperature; therefore, charge state measurement methods should take temperature into account. There are usually specific applications for alkaline batteries and other applications for lithium batteries [7].

E. Battery Usage Considerations

Battery performance is affected by several factors, especially temperature, charge/discharge rate, hysteresis, self-discharge, and cell age.

The effect of temperature on SOC and internal resistance is shown in the graph in Figure 3. This comes from a test performed from 0°C to 45°C, where the battery is discharged for the first time at 10% of rated current full capacity. The battery was then left in the Open Circuit (OCV) state, considering the stationary state. The battery continues to discharge continuously at more than 10% of nominal capacity. This procedure is repeated several times [10].

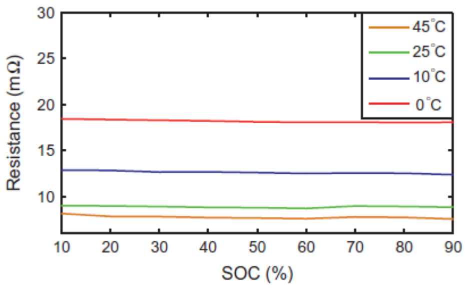

Figure 3. Effect of SOC on internal resistance to different temperature values [10].

For each temperature value, at the same SOC values, the resistance is greater in some cases than in others. For example, at 10°C and with a SOC of 20%, the resistance value is lower for the same SOC value at 45°C. This concludes that for same SOC values, the higher temperature, the resistance value is lower.

The capacity of alkaline batteries varies greatly with the effect of temperature compared to the capacity of lithium batteries. In lithium batteries, if it operates at negative temperatures, for example -20ºC, its capacity is practically the same if it operates at high temperatures of 60ºC. This comparison is seen in the graph in Figure 4.

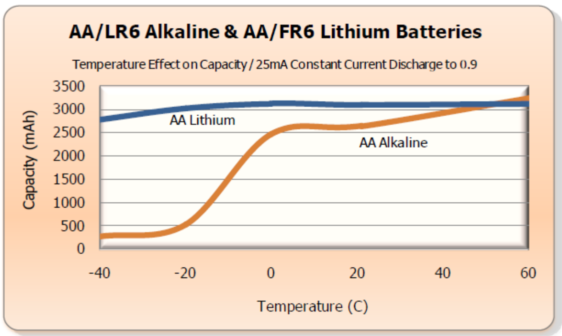

Figure 4. Effect of temperature on the capacity of different types of batteries [7]

Even discharged alkaline batteries can be stored for long periods without causing damage and recharge. The self-discharge effect consumes the available energy in the cell.

Control techniques should be applied to end the charge before an unusual increase in battery pressure or temperature occurs. These techniques are useful for avoiding overcharging, facilitating quick charging, detecting a problem with battery operation, and reducing the charge rate to safe levels. Discharge control should also be performed to maintain the balance of the batteries and to prevent over discharge.

Battery encapsulation is a consideration for manufacturers, as they must be resilient to avoid spillage. The type of enclosure may vary from the application in which the battery is intended to be used, as if the battery is exposed to a strong environment, for example outdoors or in high humidity conditions, it must have a durable housing. Usually the battery cell is sealed by a plastic zone that protects the cell from external influences and reduces the evaporation of the battery electrolyte [11]. The encapsulation of the batteries makes them resistant to vibration, aids in thermal insulation and heat dissipation.

F. State of Health

The state of health (SOH) of a battery, applicable only to rechargeable batteries, is very important to monitor its performance and achieve the intended goals of the battery, as the battery gets older, its performance is compromised. SOH is the ability of the battery to provide power over its lifetime [12]. When buying a new battery this value is 100% and its end-of-life is close to 80%. The SOH is

$$SOH = \frac{C_t}{C_{bat}} \times 100\% \tag{5}$$

And it can be calculated from battery capacity and impedance. Where C_{bat} is the initial battery capacity and C_t is the current battery capacity at time "t".

There are several indicators that may reflect battery performance and aging, such as capacity and impedance, charge state, available power, and remaining battery life (RUL). Capacity is the capacity of the battery to store energy and it decreases over the life of a battery due to its aging. On the other hand, with aging, the impedance of the battery increases [13]. Available battery power is a direct indicator of battery performance, limited by its voltage, current and temperature. Remaining battery life is the number of charge/discharge cycles before the battery reaches 80% SOH [12]. This factor depends on the type of battery and its usage mode. The mode of use of a battery varies from the device the battery powers and the user's use of that device.

G. Existing Instruments - Simulators

Battery simulator is an electronic device, designed to test battery charges of any voltage and power. The simulator eliminates the need to connect a battery to the charger to be able to test it and allows to know the state of the battery to perform maintenance. The simulator simulates the characteristics of the battery and is like a power supply that generates positive voltage and current. The simulated battery voltage can be set manually or via computer. Typically, simulators have integrated voltage and current monitoring. Basically, the user selects the battery voltage that he wants to simulate while the value is displayed on the digital display. The most common applications when using a simulator are simulating the state of charge of a battery during charging or discharging, testing a battery-powered system, replacing the real battery with the simulation, and testing the battery charger by eliminating the need to connect it to the actual battery. With a battery simulator it is possible to perform tests quickly, safely and accurately.

For example, simulators like Keithley's 2281S Battery Simulator and Precision DC Power Supply and ITECH's IT6400 Bipolar DC Power Supply Battery Simulator.

With the Keithley simulator it is possible to simulate a battery with the functions of a high precision power supply, analyze the DC consumption of a device under test, test a battery, and generate a battery model based on battery charging process and simulate a battery based on the battery model. This simulator has a linear regulation to guarantee low power noise and superior load current measurement sensitivity. The user interface is easy to navigate because it is made up of a high-resolution color screen and displays a large amount of information about the measurements, as observe in Figure 5. These characteristics allow to optimize the speed of the tests.

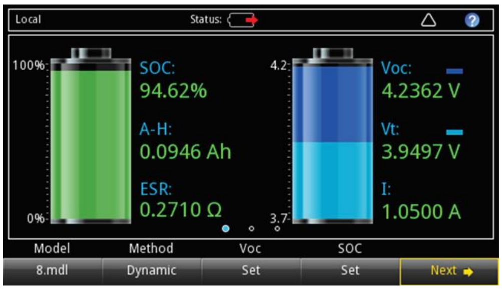

Figure 5. Battery Simulator example of home screen. [5].

One of the applications consists of simulating a battery based on a battery model, using the state of charge and the open circuit voltage (V_{OC}). For this it is possible to choose two modes, static, in which during the simulation the SOC and V_{OC} values don't change, or dynamic, the SOC and V_{OC} values change according to charge/discharge. Another application is to determine the state of charge and internal resistance (ESR) and create a battery model.

In the test mode the charge / discharge test of a battery is carried out and this determines the battery capacity and the ESR value automatically. This generates a battery model based on the results measured during the charging process. In the simulator, the battery model can be edited, imported and exported in the format of a CSV file.

The IT6400 is composed of several models (IT6411, IT6411, IT6412, IT6431, IT6432, IT6433, IT6432H and IT6433H) that differ in voltage variation, current variation, power and number of channels.

Like the Keithley simulator, the ITECH IT6400 simulator has the same functionalities. The main features of the ITECH simulator consist of having oscilloscope waveform display function, battery simulating function, ultrafast transient time less than 20 microseconds, function screenshots and DVM test function.

III. BATTERY EMULATOR

A. *Requirements*

For the realization of this system it is necessary to analyze several parameters that determine the operation of a battery. For this purpose, an analysis was made of different alkaline and lithium batteries, like AAA LR03XWA Panasonic [9], AA LR6XWA Panasonic [15], C LR14 Energizer [16], D LR20 Energizer [17], CR123A Panasonic [20], AA L91 Energizer [18] and AAA L92 Energizer [19]. The nominal voltage, the discharge point and the internal resistance variation for each of them were determined, and thus the system requirements were obtained, presented in Table I.

TABLE I. SYSTEM REQUIREMENTS TABLE

Supply Voltage	12 V
Output Voltage	9 V
Minimum Output Voltage	0.9 V
Minimal and maximum Internal Resistance	0.065 Ω - 16 Ω
Voltage Resolution	10 mV
Resistance Resolution	75 mΩ
Minimum and maximum current	0 – 500 mA

B. *Architecture*

The purpose of the system developed is emulate a battery. For this, it must contain circuits that allow both voltage and output resistance to be regulated by emulating a battery. The architecture selected, shown in Figure 6, uses the ESP32 processor for control functions.

Software will be implemented to develop the system using the ESP32 microcontroller. The ESP32 consists of two processors, has Wifi and Bluetooth communication, runs 32-bit programs and can be connected to various peripherals, such as ADCs, DACs, UART, SPI, I_2C, among others. Its clock frequency ranges up to 240 MHz and has 512 kb of RAM. In addition, ESP32 can be programmed in a variety of development environments, such as Arduino IDE, JavaScript, Python, among others [21]. The ESP32 processor is chosen because of its amount of RAM and the amount of flash that allows storage of battery models, DACs and ADCs.

The solution for this project includes the use of Silicon Labs CP2102 USB Bridge which consists of a single integrated circuit that allows the transfer of UART data from USB connection. The CP2102 is used because the ESP32 processor supports UART communication and a connection between the processor and the user interface on the computer is required. The Power Management block is a system function that will be responsible for converting the 12 V input voltage to the levels required to operate the ESP32.

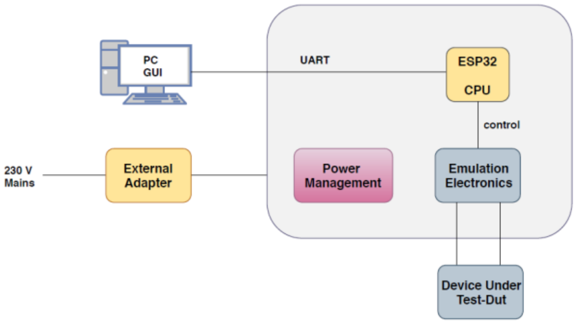

Figure 6. System architecture.

The implemented architecture, Figure 7, includes the use of a digital to analog converter (DAC), a DC-DC converter, several pmos transistors and several resistors in parallel. The DAC will control the feedback loop of the DC-DC converter and with it control the voltage level at its output. The architecture includes the spent energy count, called the Coulomb count. This is implemented using a sampling resistance of approximately 0.1 Ω on the positive side, a shunt amplifier, and an analog-to-digital converter (ADC). This count is made by reading the ADC and calculating the output current by compensating the ADC reading for the amplifier gain and resistance applied to it (0.1 Ω). This lets we know which SOC needs to discharge and which current has been measured constantly. The proposed system includes signal generation, processing, acquisition and battery emulation.

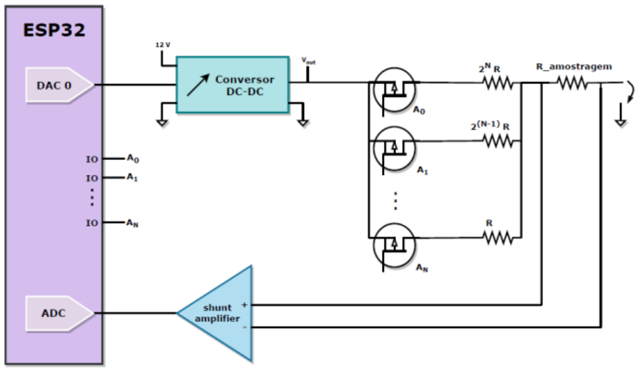

Figure 7. Battery emulation circuit.

The variation of the output resistance varies according to the digital value of each control bit like the equation

$$\Delta R = \frac{1}{\overline{BIT_1} \times \frac{1}{R_1} + \overline{BIT_2} \times \frac{1}{R_2} + (\ldots) + \overline{BIT_8} \times \frac{1}{R_8}} \quad (6)$$

Where the control bit may be set to 0 or 1 depending on whether the resistor is connected in parallel or not. If it is connected in parallel, the control bit takes the value 0, if not 1.

After defining the solution for this project, made up a simulation for the presented architecture. A network with 8 resistors and 8 parallel transistors was defined that varied the output resistance according to an 8-bit binary code. Resistors of 16 Ω, 8 Ω, 4 Ω, 2 Ω, 1 Ω, 0.5 Ω, 0.25 Ω, and 0.125 Ω were used. Thus, using (6) it was possible to determine the value of the internal resistance and the resistance resolution for each code, which in decimal ranges from 0 to 256. The resolution is determined from the resistance difference between two consecutive codes. By simulating the circuit, we obtained the graph of Figure 8.

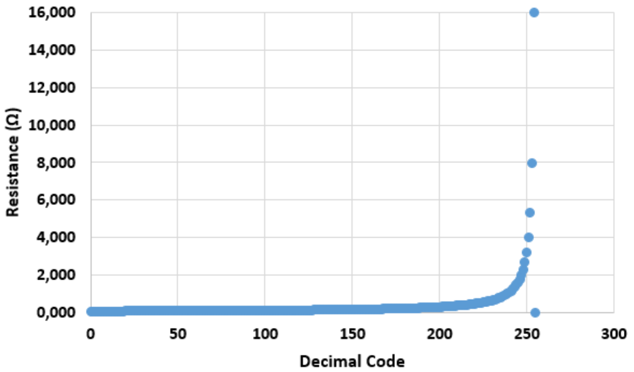

Figure 8. Variation of internal resistance with code.

By analyzing the graph in Figure 8, we observed that with increasing codes, the resistance also increases. Approximately up to code 200 the resistance increases gradually and from there it has already increased more sharply. However, when the resistance increases there is a point at which the resolution becomes worse than the resistance resolution value proposed in Table 4 on system requirements.

C. *Hardware*

The proposed system architecture is divided into four main blocks. The first consists of the part composed by the DC-DC converter that aims to regulate the output voltage, the second consists of the amplifier, the third comprises the resistor and transistor network responsible for regulating the output resistance and finally there is a module to regulate the tension. For the first part, with the electrical schematic shown in Figure 9, a Buck converter is chosen, which has the AP1513 as it has an input voltage of 12 V and a maximum output current of 1 A. This converter is supplied in package SO8 and choose this package because there are multiple compatible references. In addition the converter needs an additional circuit for its operation, which consists of an input capacitor and a 470 μF output capacitor, three 0.1 μF capacitors, a zener diode (SBR2U30P1), five 3 kΩ resistors , 100 kΩ, 6.8 kΩ, 1kΩ and 1.3 kΩ respectively and by a 33 μH coil [23]. These components are for low current draw and are current limiting.

Resistors R_{20} and R_{28} were calculated according to the desired value of V_{out} and the value of the feedback port voltage (V_{FB}). This is given by

$$V_{out} = V_{FB} \times (1 + \frac{R_{20}}{R_{28}}) \Leftrightarrow 9 = 0.8 \times (1 + \frac{R_{20}}{1.1k\Omega}) \quad (7)$$
$$\Leftrightarrow R_{20} = 12k\Omega$$

Knowing that R_{28} could range from 0.7 Ω to 5 kΩ. Thus, in order to be able to combine the possible resistances that were available it was stipulated that R_{28} would be 1.1 kΩ.

Regarding the amplifier block, the chosen amplifier is the AD8418 –Bidirectional, Zero Drift Current Sense Amplifier because the supply voltage ranges from 2.7 V to 5.5 V and the gain is fixed with value 20. In addition, it has an operating voltage range from -2 V to 70 V in common mode. The AD8418 is intended to operate in bidirectional operating mode, i.e. output adjustment is performed by applying voltage to the referenced inputs that are connected to resistors R_{41} and R_{43}. One of the pins is connected to the V_{DD} and another to ground, so that the output is adjusted to half of the source value when there is no differential input, because if the source increases or decreases, the output remains at half [22].

For the resistor network the package SOT223 transistor DMP2120U is chosen, as it has a low resistance of 62 mΩ and 90 mΩ. Although it was necessary to add 10 kΩ pull-up resistors to the gate of each transistor, because when the transistor is to be turned off the gate must be at the potential of the drain and its V_{GS} must be zero. In the left zone of the grid were also added 10 kΩ resistors connected to V_{in} and V_{out} and an NPN PMBTA42 transistor between the 1 kΩ and 10 kΩ resistors. This is because the input and output ports of the processor will work in two ways: when we want turn off the resistance, we will have a logic value of 0, and for this, the NPN transistor operates in the cutoff region with 0 V at the base and the PMOS is turned off, also put into operation in the cutoff region; to turn on the resistance, we will have a logic value of 1, and for this to happen, the NPN transistor is saturated with 2.8 V at the base and PMOS works in the triode region.

The voltage regulating module consists of the LM317DCY - Adjustable Terminal Regulator with a variable output voltage between 1.5 V and 37 V [24]. The circuit for common applications provided by the supplier specification document requires two external output resistors, one 240 Ω (R_{42}) and one variable (R_{44}) [24]. The variable resistance, R_{44}, depends on the value of $_{VDD}$ and is obtained from

$$V_{DD} = V_{REF} + (1 + \frac{R_{44}}{R_{42}}) \quad (8)$$

Since V_{DD} takes the value of 3.3 V, V_{in} is 12 V and so R_{44} should be 393.6 Ω.

After the implementation of these circuits the respective two-layer printed circuit was developed like in Figure 9, both with green welding mask and with a dimension of 70 x 75 mm.

The highlights of Figure 9 correspond that module 1 refers to the DC-DC and DAC converter, module 2 to the amplifier and the ADC acquisition circuit, module 3 consists of the ESP32 chip, the crystal and components required for its operation. In operation, module 4 is the transistor and resistor network, module 5 concerns the voltage regulator and finally module 6 is for connecting the headers for user interface communication and for data passing via R_X and T_X. After testing the various modules of the board, the ESP32 evaluation board was used as a test circuit only.

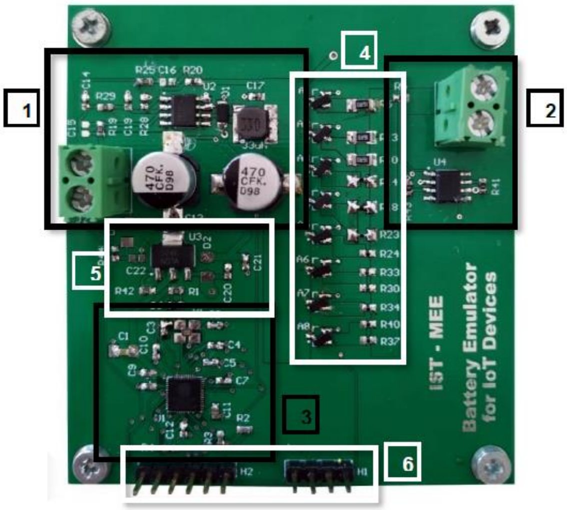

Figure 9. PCB developed.

D. Firmware and Software

A Python user interface was developed using TraitsUI, as shown in Figure 10. TraitsUI is a Python module designed for programming graphical applications, where data and parameters are stored in objects as the user interface reflect the projected code [14]. The interface allows a better user interaction with the program, making it simpler, faster and more intuitive. Traits are made up of modules and subpackages that sometimes need to be used for the correct operation of the user interface and implementation of functions.

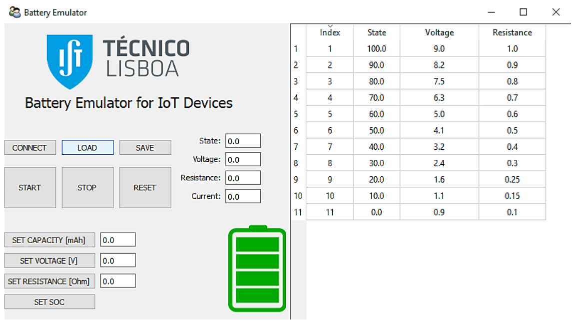

Figure 10. GUI in Python.

The interface is made up of a total of ten items, four numeric indicators, a table with battery change parameters and a picture of the state of a battery. The first three items are the main buttons, and "CONNECT" serves to initiate serial communication; the "LOAD" button opens a directory where the .csv file with the battery data exists. The file is validated and the data (load state, voltage and resistance) are presented in the table in the interface. If the user needs to change any of these values, you can do so and then use the "SAVE" button to save the file with the necessary changes. The "START", "STOP" and "RESET" buttons are the main buttons for controlling the battery, as "START" starts discharging the battery, "STOP" finishes discharging the battery whatever are the SOC. The button "RESET" returns the battery to 100% of its charge state. In order for the user to be able to discharge the battery and count the current, he needs to send the battery capacity in mAh. In addition, it is possible to control the desired voltage and resistance, where the voltage can range from 0.02 V to 9 V and the resistance from 0.063 Ω to 16 Ω. These functions are performed by the "SET VOLTAGE" and "SET RESISTANCE" buttons. However, the user can also control the battery by the charge state value if this value is already in the table. Simply select the desired value using the "SET SOC" item.

As communication is performed during battery discharge, a timer was used for the numeric indicators to display the values of the charge state, voltage, resistance and current throughout the discharge. Finally, the battery image changes according to charge state values, which can be 100% to 85% green, 85% to 60% yellow, 60% to 35% orange, 35% to 5% red, and from 5% onwards it becomes the image of a battery with a charger.

As noted, the user interface communicates over a serial port by sending and receiving commands to the device. For this purpose, functions were received for receiving commands, processing commands and sending commands, both on the interface side and on the device side.

For this communication to be carried out it was necessary to implement value conversion functions for fixed point and float format. This is because sending data from the user interface is done by integer values and practically all values used in the program are of float type. For this reason, before some values are sent, they are converted to a fixed point and after received they are converted to float again. Battery emulation is performed from one thread. We created a set of shared variables that are used for communication between the two execution loops. The ESP32 firmware was developed in C++ language and comprises three .cpp files important for its operation. These files consist of the main program (main.cpp), the serial communication program, and the battery emulation program. Each program had its main functions implemented, with specific objectives.

E. Experimental Results

The first test to be realized was the test for the characterization of the output resistance. This consisted of programming the various resistor values corresponding to 256 binary codes while the system was supplying a constant voltage of 9 V. The voltage in the transistor and resistor network and the output voltage were measured. With these values the output current and thus the actual output resistance was determined. This comparison is observable by Figure 11.

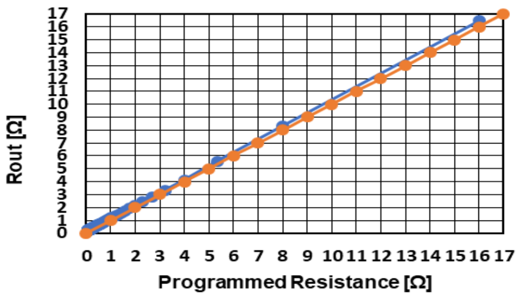

Figure 11. R_{out} variation according to programmed resistance.

From the graph of Figure 11, we concluded that the values obtained of resistance are close to the programmed values. However, for lower resistance values, these have only a small difference of approximately 0.1 Ω more than the programmed values, as this is the shunt amplifier's sensing resistance. For higher values, such as 8 Ω and 16 Ω, this difference is almost 0.5 Ω. These approximations are observable because the blue curve should correspond to the orange curve, which would be the ideal case, where the output resistors took the exact value of the programmed resistors. However, there is a quick distance, but the results are close to those expected.

In addition to the output resistance control test, a second test for characterization of the output voltage was also performed. In this case, 256 possible DAC values were varied to obtain 256 different voltage values while maintaining the lowest output resistance value (0.063 Ω). Thus, we obtained the graph of Figure 12 that represents the variation of the output voltage with the increase of the codes imposed for the DAC.

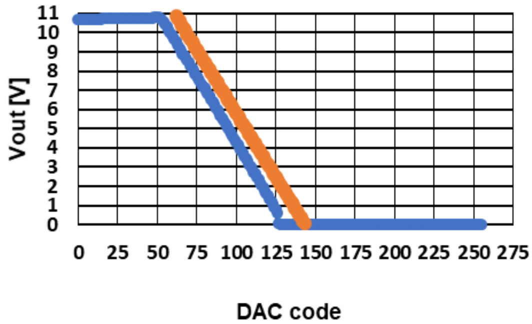

Figure 12. V_{out} variation as a function of DAC codes.

As the DAC code increases, the output voltage value decreases to zero. By analyzing the experimental curve in blue, we can be concluded that up to approximately code 125 the voltage value remains constant around 10.7 V. These values are close to those expected because the expected voltage curve is verified by increasing the codes of the DAC the voltage decreases. However, the curves differ in the sense of their starting point and ending point, as V_{out} should start to decrease from code 60 approximately, and in reality decrease from code 50. This is because exist an offset, but the results are as expected.

Along with the second test measurements were taken to compare the theoretical and practical current values. The theoretical current value is the value calculated by the software according to the voltage that is read from the ADC. The practical current value was obtained by measuring the previous test, knowing that the resistance would be constant 0.063 Ω with the load 120 Ω and the voltage values varied with the DAC code. Thus, we obtained the graph of Figure 13 which represents the variation of both currents with the increase of the DAC code.

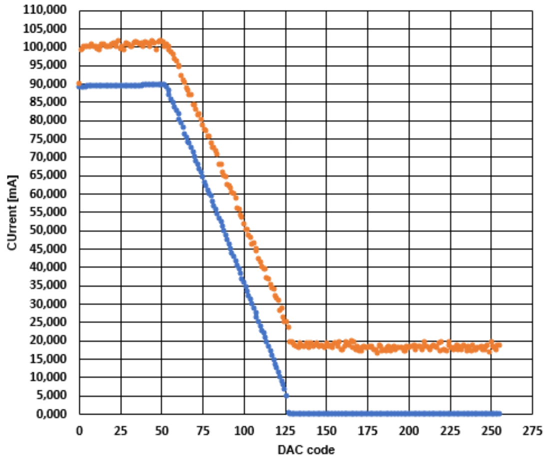

Figure 13. Variation of the theoretical and experimental current with the variation of DAC.

In Figure 13, the orange curve is the theoretical current and the blue curve is the experimental current. Both currents decrease with increasing DAC code, ie with decreasing output voltage, which makes sense because the resistance value is constant, and the current must accompany the voltage decrease. Regarding the comparison of the practical current with the theoretical current, there is a discrepancy of values in the order of approximately 10 mA, mainly during the variation of the first 50 codes. From there both currents decrease identically and from code 125 remain constant. At this time, they have a difference of 20 mA. This happens at the moment when the output voltage drops to 0 V. The larger the current, the greater the difference between the theoretical and practical currents. For lower currents these are identical, but for higher currents the theoretical current tends to be twice the practical current. This difference in values is due to the fact that the ADC is nonlinear, has read errors and its reference voltage can vary until to 1.16 V. Attempt to correct this ADC nonlinearity during firmware development by averaging the values. read by the ADC. In addition, the system has been programmed to perform a calibration when it is started, that is, it deactivates all resistances and reads the voltage of the ADC, which is called offset. Thus, in the next ADC readings, with different resistance values activated, the offset is subtracted to make the system as close as expected. However, this was not enough to work around this problem.

F. Battery Simulation

In this section we used the data acquired from the battery specification documents and simulated for the cases: one AA LR6XWA alkaline battery, two AA LR6XWA alkaline battery, one CR123A lithium battery and two CR123A. In the first case, the 2800 mAh alkaline battery and two AA LR6XWA batteries of the same capacity discharged for approximately 9 hours and 50 minutes. One CR123A lithium battery with capacity of 1550 mAh discharged for 4 hours and finally two of CR123A discharged for 2 hours and 30 minutes. In all cases 10% of the charge state was discharged, ie until the battery reached 90%, since there was no time for more. Firstly, the alkaline batteries were discharged, which can be seen from Figure 14.

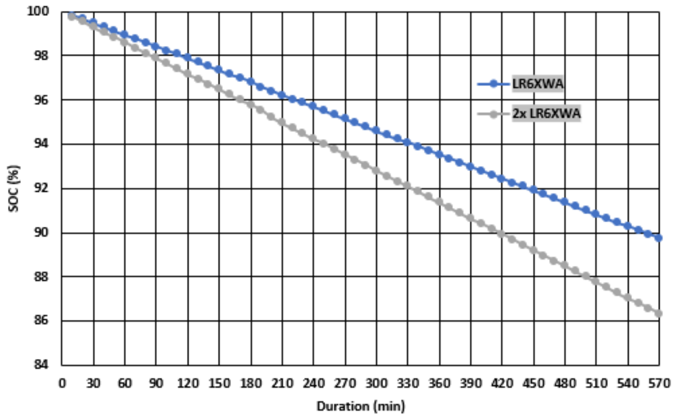

Figure 14. Variation of SOC of alkaline batteries.

Two AA LR6XWA batteries are found to achieve 90% faster SOC than one LR6XWA AA battery. The difference between these is the voltage and resistance with which they began to discharge, as the 2x LR6XWA had 3.2 V and 0.16 Ω for a 100% SOC, while the LR6XWA had half of these values for 100%. It follows that two series alkaline batteries discharge faster than just one alkaline battery.

In addition to SOC, the current was also analyzed during discharge and although the batteries started discharging with 100% SOC and with different voltage and resistance values, as the 2x LR6XWA started at twice the values of LR6XWA, its current at the length of the discharge should be the same. This is not the case, however, although the rate of change is approximate, for until approximately the first three hours, both currents remain constant and then make a slight decrease, eventually increasing again for a short time. In addition, both decrease in the final hours of analysis. The difference between the currents may be due to the fact that there is offset in the reading of the ADC values. Even trying to compensate for this value in the firmware programming, when starting the system, it was not the same for discharging these batteries.

After analyzing the alkaline batteries, the lithium batteries were discharged, and it was possible to observe the change in charge state over time from Figure 15.

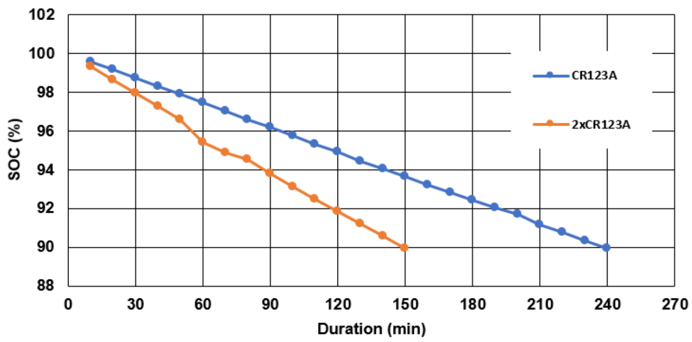

Figure 15. Variation of SOC of lithium batteries.

We observe that the 2x CR123A battery has reached 90% of charge state first than the CR123A battery. In this case, the 2x CR123A battery also started to discharge, with 100% SOC, with voltage and resistance values twice the CR123A battery. The first one started with a voltage of 6 V and a resistance of 0 Ω, which by our system changes the resistance to 0.063 Ω because it is the lowest resistance value that the system can generate. Thus, it follows that two series lithium batteries discharge faster than just one lithium battery.

For comparison of the voltage variation over the hours, the CR123A battery specification document was used and the expected voltage values were practically constant, since for almost 2 hours and 50 minutes it should be practically 3 V and thereafter it decreases linearly to 2.75 V, which becomes constant until the end of the discharge. Experimentally there are some variations in voltage and it does not decrease linearly, as it has to be taken into account that the generated voltage is realized by the DAC and it has little resolution. The biggest difference is that the voltage does not decrease abruptly, but gradually decreases along the discharge. Despite this, at the end, after 4 hours, the voltage value is very close to expected. We did the same for the 2x CR123A battery and the result was the same. The analysis of lithium battery currents occurred as the analysis of alkaline batteries.

G. Conclusion

Analyzing the differences and functionality of batteries and the applications of battery simulators, it is concluded that using a battery simulator there are more advantages than continually performing battery tests. The biggest advantages of using a simulator are that the simulator decreases test time, provides repeatable test results, improves safety, provides digital visualization of results and the user does not have to worry about lifetime. Battery By simulating a battery, the user has control over the voltage and current they want and the output resistance they want, quickly and simply.

This work presents an architecture for the emulation of a battery, using the ESP32 processor as a control device, in which software was developed to implement the system. This architecture encompasses circuits that allow you to regulate output voltage and resistance by emulating a battery, so you can study the consumptions of IoT devices.

Regarding the final results, the voltage, resistance and current values obtained with the generation of the different DAC codes and the possible resistance values are within the expected range. There are only a few discrepancies due to ADC nonlinearity and little DAC resolution.

We concluded that a solution with all the implemented functionalities could be developed even with some limitations in terms of the reached specifications. In the future it is possible to develop some proposals, for example the use of ADC and DAC external to ESP32 to improve the resolution and accuracy of voltage generation and current measurement. In terms of testing and analysis of results, it is later of interest to discharge more batteries, with different characteristics in which it was verified how long the state of charge eventually reached 30% for example, as well as the voltage curves. and current during this discharge. These comparisons could be made using theoretical solutions and previsions of the time the battery would discharge and its voltage and current values.

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