

# MAXIMIZING THE MANAGEMENT EFFICIENCY OF RECHARGEABLE BATTERIES IN CRITICAL ENERGY STORAGE APPLICATIONS

## PhD thesis - Abstract

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# **1. Introduction**

## **1.1. Field and topic of research**

The unprecedented technological progress that mankind enjoys today would not have been possible without certain essential components - rechargeable batteries. Currently, the most used technology is that of rechargeable Lithium-ion batteries. A relatively new class of battery-based applications is that of critical energy storage applications (electric vehicles, backup data storage systems for data centers, etc.). The main topic addressed by this thesis is to reduce the degradation of rechargeable Li-Ion batteries. Although most battery management systems (BMS) in critical energy storage applications implement battery balancing mechanisms, in practice a premature degradation of the component batteries is observed. The reconfigurable connection topology is a recent alternative, but the problem of maximizing the lifespan of these systems, while reducing the total cost of use is incompletely solved. In this thesis we started from the observation of the analogy between flash memory and reconfigurable battery packs (RBP) to develop a method based on the principles and algorithms of wear leveling, called BWL. The method was integrated into a BMS designed by the author for RBP, and a comprehensive methodology was developed to evaluate the system. By analyzing the BMS performance that integrates the BWL method compared to conventional BMS implementations, its viability and superiority was demonstrated in all scenarios considered.

Rechargeable batteries are complex electrochemical systems, being essential components for today's increasingly rapid technological progress. Sony introduced the first rechargeable Li-Ion battery in 1991, and since then the market for these batteries has seen tremendous growth. At present, rechargeable lithium-based batteries are by far the most widely used, to the detriment of older technologies [1]. A disadvantage of Li-Ion batteries is that the remaining life (RUL) or equivalent size - the state of health (SoH) is directly dependent on the temperature, the size of the charging / discharging current, and the State-of-charge (SoC). Therefore, every Li-Ion battery in a consumer device contains a protection circuit inside.

Industrial applications such as electric vehicles, backup energy storage systems (UPS) for data centers, or storage systems connected to the electricity distribution network are just a few examples of applications that are increasingly using Li-Ion batteries. These applications require battery management systems (BMS) with high requirements for scalability and reliability. Recent research in the field has led to the emergence of the reconfigurable battery pack, which allows dynamic adaptation to the load and increased reliability, through the possibility of disconnecting and isolating problematic batteries. However, the efficient management of reconfigurable battery packs used in the above-mentioned applications remains an unresolved issue.

## **1.2. Motivation and objectives of the research**

Battery state of health (SOH) is usually defined as the ratio of current battery capacity to new battery capacity at a discharge rate of 1C [2]. As the lifespan can decrease rapidly if the battery is used improperly, the problem of managing rechargeable batteries as efficiently as possible is a topical one and the number of articles published in this field is growing. In applications that use rechargeable batteries, the main component of the operating cost and the main reason for decommissioning, is the premature degradation of the batteries. Several methods for reducing degradation are described in the literature, but some are too complex to be implemented in embedded systems while others do not take into account all aspects of cost or reliability. There is a high scientific interest in the relatively new field of RBP, but few articles present a complete analysis of the costs and benefits of a practical implementation.

The main objective of the research underlying this work is to bring contributions to improving the management efficiency of rechargeable batteries in reconfigurable energy storage systems [3]. In this sense, the initial idea from which to start is to study the possibility

of applying flash memory (wear leveling) methods to the field of batteries, based on observing the analogy between the degradation of flash memory cells and the degradation of Li-ion batteries.

The second objective of the doctoral research is to develop a programmable system for managing rechargeable batteries in order to reduce the total cost of use.

### 1.3. Thesis structure

The doctoral thesis is structured as follows:

- Chapter 2 reviews the current state of the art for: types of models for SOH estimation and prediction, solutions and commercial circuits for SOH estimation, reconfigurable battery packs, BMS systems, classification of existing BMS architectures.
- Chapter 3 introduces the method proposed by the author to minimize battery degradation. It presents the current state in the field of wear leveling in Flash memories and a comparative analysis is made between the concepts of Flash memories and those of battery packs. The principles of the proposed BWL system and those of a BMS based on this method are then described.
- Chapter 4 presents the methodology used in the research undertaken for this paper.
- Chapter 5 presents the results obtained by running the simulation scenarios described in the previous chapter but also the results of applying the proposed method on a publicly available data set.
- Chapter 6 presents the practical implementation of a minimal BMS, on a series of hardware and software platforms, both desktop PC and embedded.
- Chapter 7 concludes the paper, describes a summary of the main contributions presented in the thesis and reveals some ideas for possible further research.

## 2. The current state of research

High-capacity energy storage systems can be found in industrial, commercial or household applications, which contain a large number of rechargeable batteries, thus having high operating and maintenance costs. The large number of articles published in the field of maximizing the life of rechargeable batteries demonstrates the interest of the scientific community in this incompletely solved problem. Accurate determination of battery degradation degree in order to estimate lifespan is very important from a technical and economic point of view.

One of the most used battery models is the electrical equivalent [4] or  $n$ -th order Randles. A variant derived from it is the electrochemical model, which is generally more complex due to the approximation of electrochemical processes in the phases of relaxation, discharge and charging [5]. The mathematical model describes the dynamic behavior of the battery based on empirical relationships between artificial parameters, without a direct connection with battery physics. In the literature there are also models based on the life cycle, which monitor the long-term operating parameters of the batteries [6].

With the development of the battery-powered device market, stand-alone integrated circuits and solutions have emerged that facilitate battery management [7]-[8]. Among the manufacturers of such solutions, we can mention: Texas Instruments, Maxim Integrated, ST Microelectronics, Analog devices and HDM Systems. A general feature of commercial solutions is that the estimation methods used are generally based on relatively simple electrical models, and most manufacturers do not provide implementation details. The performance of these solutions is acceptable, but generally inferior to the more advanced methods in the literature.

The degradation modeling in arbitrary usage conditions is approached in the electric-mathematical battery model from [9], based on the phenomenon of crack propagation in the electrode structure. From the experimental data presented in the article, it can be concluded that

the proposed model has a high accuracy and faithfully follows the real behavior of the tested batteries. It is also relatively easy to adapt to other types of Li-Ion batteries.

Energy storage systems use a large number of batteries to achieve the power and energy objectives required by the application. In most cases, the batteries are connected in series and / or in parallel in a static topology. The main disadvantage is that variations in individual batteries will cause capacity reduction and premature decommissioning over time. Reconfigurable connection schemes have generated increasing interest from researchers in recent years, thanks to the advantages over conventional connection schemes: the connection topology can be changed dynamically during use, based on real-time load conditions. A series of reconfiguration topologies have been proposed in the literature: JPL [10], series [11], DESA [12], graphs, etc.

A notable degradation minimization solution is SHARE [13], which proposes grouping together the batteries with similar SOH, in a JPL configuration. The CSR method [14] selectively omits batteries to optimize the energy supplied and is also based on a JPL configuration. Although these solutions show results in reducing battery degradation, the performance is generally low and the algorithms used are too complex to be implemented in an embedded BMS.

In the field of BMS architectures there are several representative models, and the most widespread is the hierarchical type architecture, having scalability, flexibility and fault tolerance as main advantages. Another classification of BMS is shown in Figure 1.

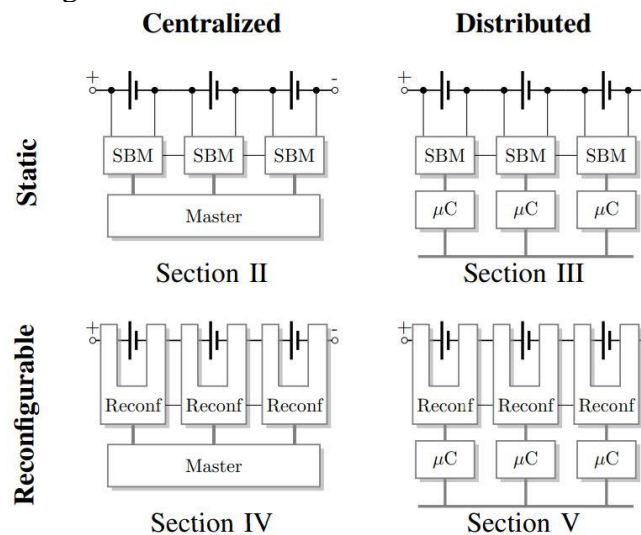


Figure 1 Classification of battery management architectures [15]

This classification model is realized according to the topology of organizing the batteries in packs, which can be static or reconfigurable, respectively the centralized or distributed organization of the BMS structure [15].

### 3. Method to minimize battery degradation

#### 3.1. Wear leveling in Flash memories

The most popular current products that employ flash memory are solid-state disks (SSDs), SD cards and eMMC cards. They have several advantages over hard drives: speed, reliability, low power consumption. Because Flash memory blocks cannot be rewritten without prior deletion, the connection between the Flash array and conventional file systems is made through the Flash Translation Layer (FTL) [16]. Due to the limited number of erase and write cycles, FTL must ensure the most uniform allocation of all blocks through *garbage collection* and *wear leveling* techniques. There are 2 types of wear leveling: dynamic (for frequently accessed data) or static (for all data - allows achieving uniformity of degradation).

The first strategies of write wear leveling used only dynamic data, but overall performance is low, because on average, only 25% of memory capacity is occupied by dynamic data. Among the existing principles and algorithms of static wear leveling we can mention:

- Static wear leveling [17]: SWL, HaWL, RRWL
- Hot-cold swapping: Group WL [18]
- Cold-data migration: dual-pool, remaining-lifetime, lazy wear leveling (LWL) [19]

The authors of LWL want to alleviate the shortcomings identified in the existing solutions, and the proposed method can be well integrated with the standard garbage collection implementation in FTL. Thus, wear leveling only runs triggered by garbage collection because FTL will only delete blocks after garbage collection runs. The evaluation results show that the proposed algorithm is more efficient than the existing ones, in almost all cases.

### **3.2. Battery pack – Flash memory analogy and the principles of the BWL method**

The analogy between the two technologies can be seen from several perspectives, even if not all the characteristics can be equated:

- structure: array of blocks vs. array of batteries
- write - erase cycle management vs. charge – discharge
- free / occupied space vs. available / consumed capacity (SOC)
- garbage collection vs. recharge batteries used in previous cycles
- static wear leveling, block replacement vs. charge migration, battery replacement

Based on these observations, the Battery Wear Leveling (BWL) method was developed, which has the following guiding principles:

- is intended for critical energy storage applications (1k - 100k + batteries)
- acts on a reconfigurable array of batteries (JPL type, possibly other types)
- the number of connected batteries is  $f(\text{consumer load})$ ; spare batteries: 5%
- reconfiguring the array is done before the discharge phase
- the charge phase is an extension of the discharge phase
- battery reconfiguration and reallocation: based on the static wear leveling algorithm LWL [19]
- operating schedule is known a priori (e.g.: electric car, differentiated energy pricing)

A BMS that manages a reconfigurable battery pack, based on the proposed method, can be designed as a dedicated SW solution on an embedded platform. It must be an autonomous system that can calculate SOC and SOH online and will integrate the BWL method to minimize degradation over time. Structurally, it is composed of several interdependent functional blocks shown in Figure 2, among which we mention SOC estimation (obtaining *SOC\_start* per battery) and SOH estimation (degradation model application, BWL application, switch control, external systems interface).

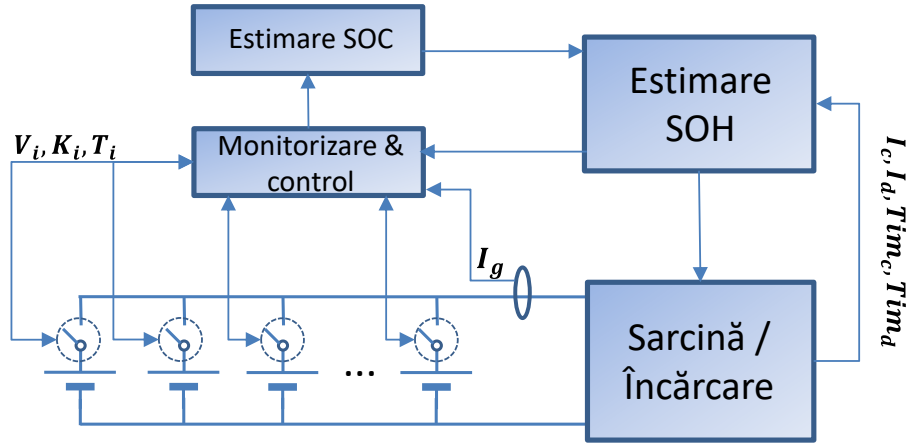


Figure 2 Proposed BMS high-level schematic

Passive circuit elements, such as switches and fuses, have a significant influence on the cost, volume occupied and performance of the energy storage system [20]. In the existing BMS implementations we find electromechanical or semiconductor relays. Semiconductor relays have a number of advantages: reliability, size, small switching time. In their case, the loss of power occurs mainly in the switching phase. The degree of reconfiguration of the battery packs is influenced by the number of switches, which imposes limits on the dissipation of residual heat, increasing the physical dimensions of the system and the switching latency, which leads to performance degradation.

### 3.3. BWL method implementation

Assuming that the charging phase is complementary to the discharge phase, the selection of batteries based on the LWL substitution algorithm takes place only in the discharge phase. The calculation of the score of each battery in the pack for selection is done by applying the formula  $L_{scor}(b) = \omega_{SOC} \cdot G_{act}(b) \cdot SOC + \omega_{SOH} \cdot G_{act}(b) \cdot SOH$ , with equal weights for SOH and SOC.

The core of the BWL method is detailed in the excerpt below:

- 1: **while** ( $I_g^{max} < I_d$ )
- 2:  $b \leftarrow top(L_{scor})$
- 3: **if** ( $(SOH_{avg} - b.SOH) > SOH_{delta}$ )
- 4:  $b' = obtineBatBWL(b)$
- 5:  $G_d \leftarrow G_d \cup b'$
- 6: **else**
- 7:  $G_d \leftarrow G_d \cup b$
- 8: **end if**
- 9:  $I_g^{max} \leftarrow I_g^{max} + I_b^{max}$
- 10: **end while**

The loop stop condition expresses the physical condition imposed on the battery pack: the maximum current supplied by the pack  $I_g^{max}$ , is greater than or equal to the estimated load current for the next cycle ( $I_d$ ). In the first step, modeled after the garbage collection algorithm, the element (battery) is extracted from the head of the  $L_{scor}$  list. In steps 3-8, the selected block / battery is replaced (if possible) with a new block / battery, if the degradation of the original block / battery is higher than the average by more than a predetermined threshold. Then, the maximum current that the battery pack can provide  $I_g^{max}$  is recomputed in step 9 and step 10 concludes the loop.

The charge algorithm runs when the load is disconnected and the calculation provides a higher score for a lower SOC:  $L_{score}(b) = \omega_{SOC} \cdot (SOC_{max}(b) - G_{act}(b).SOC) + \omega_{SOH} \cdot G_{act}(b).SOH$ . The estimation of the number of batteries is done based on the history and the selection process of the batteries is simplified, in descending order according to  $L_{score}$  and according to the size of the charge current.

#### 4. Research methodology

This chapter will define the relevant criteria for the comparative analysis of the performance of the proposed method with the ones of the equivalent methods in the literature. The operating parameters of the batteries, of the proposed method, as well as of the energy storage system will also be identified and classified.

The following list of evaluation criteria is proposed:

1. Maximum amount of time in which the system is operational; the total cost of operation is directly proportional and closely related to this time.
2. The total capacity provided by the system over its lifetime, or the degree to which the load requirements of the system are being satisfied.

The proposed method was designed and implemented at the simulation level in the MATLAB development environment and, for a more relevant evaluation of the method's performance, a series of parameters was chosen, the variation of which generates the proposed simulation scenarios. These parameters can be classified into two categories, depending on their nature:

1. Physical parameters, the variation of which is related either to a certain physical quantity or to the physical configuration of the battery pack;
2. Calculation parameters, or algorithm parameters, the variation of which will be discussed in the context of the implementation details of the algorithms that make up the BWL method.

In order to thoroughly investigate the effects of the proposed method, it is necessary to model as accurately as possible the batteries considered in the tests performed. In this paper it was decided to model the Panasonic NCR18650A batteries ( $Q_{nom}$  3.07 Ah, 500+ cycles). The simulation of the considered battery characteristics is based on the hybrid capacity degradation model detailed in [9].

In each of the parameter variation scenarios, detailed in the next chapter, the results obtained in the following 3 operating modes will be compared and discussed:

1. reconfigurable battery pack with the application of the BWL method
2. reconfigurable battery pack without applying the BWL method
3. static battery pack, in which all the batteries are used in each cycle.

The end-of-operation condition will be the same in all modes: the system can no longer support the load at the required current and for the required time period. The implicit organization topology of the studied battery pack was established at 64 strings connected in parallel, each string containing from 1 to  $n$  individual batteries. For each component battery in the pack, the SOH is evaluated at the beginning of each charging or discharging cycle and is also recalculated at the end of that cycle.

In the thesis we present an example in which one can directly observe the effect of applying the selection algorithm based on the weighted SOH-SOC score, within the BWL method. Thus, after less than 10% of the estimated number of cycles for this simulation scenario have elapsed, the desired wear leveling effect was achieved.

## 5. BWL method performance analysis

This chapter presents, analyzes and discusses the main results obtained by applying the simulation scenarios defined in the previous chapter. The performances of the proposed method will be analyzed, both in terms of the variation of the physical parameters of the component batteries of the pack, as well as the influence of the calculation parameters. For most of the scenarios considered, the discharge and charging current rate was set at 16C,  $SOC_{start}$  was prescribed at 75% and the duration of the discharge cycle was limited to 60 minutes. This mode of operation is similar to that encountered in practice for large energy storage systems [21].

### 5.1. Variation of physical parameters

In the case of the initial SOH variation ( $SOH_{init}$ ), the total useful operating time decreases in all 3 operating modes considered, mainly due to the decrease of the average SOH value. It can be observed that the BWL method is all the more efficient as the variation of the capacity of the batteries increases, because in operation the method tends to equalize their remaining capacities over time. As a result, the BWL method provides an optimal battery management solution within the BMS.

In the variation of the used capacity scenario, it is observed that the service life increases substantially as  $SOC_{start}$  and  $SOC_{average}$  are kept to a minimum. In practice, a balance must be struck between extending service life and system availability.

In the current variation case, 2 scenarios were considered:

- different values at each simulation run, for constant current values during a run;
- variable current from cycle to cycle.

The results show the substantial gain of the BMS reconfigurable with the BWL method compared to the classical system, which increases inversely with the value of the power absorbed by the load. There may also be an accelerated and nonlinear increase in the rate of SOH degradation as the load current increases, as the BWL method will select the minimum number of batteries required to support the load.

In the variation of the download cycle duration scenario, it was desired to simulate another mode of operation that can be encountered in reality, in which the load is variable over time due to external factors. The results show that a reconfigurable BMS implementing the BWL method allows to maintain a relatively constant total operating time under a wide range of variation of the time under load, illustrating the main effects of the proposed method, uniformity of degradation and increase of the total useful operation time.

In the change in working temperature case, it can be concluded that the rate at which the service life decreases is close to the rate of degradation specified by the manufacturer, i.e., approximately 50% with each 10° C increase in temperature. This observation allows real-time corrections to the estimates of the remaining operating time to be done.

In the variation of the topology of the battery pack scenario, we studied how the number of batteries per module influences the overall performance. We started from a number of 40 batteries that we increased with a constant step of 20 for each run, up to a maximum number of 240 component batteries. The important conclusion of this experiment is that an array of batteries based on the BWL method can be scaled and designed for any application, while an array with static topology will lose much of its effectiveness as the power requirement increases.

In the variation of the auxiliary circuit elements scenario, we studied the impact of the switches on the total operating time of the system. Thus, the parameter of interest for the present scenario is the drain-source electrical resistance of the switch in the “open” state (while the switch is on), conventionally denoted by  $R_{DS(on)}$ . The  $R_{DS(on)}$  variation was modeled from the value of 50 mΩ, with a step of 50 mΩ, up to 1000 mΩ, to include most of the values of the on-state drain-source resistance of the MOSFET type switches existing on the market. The results



show a decrease in the operating time as the value of  $R_{DS(on)}$  increases. Basically, the batteries withstand a stress (due to the increased current) directly proportional to the value of the mentioned resistance, the performance decreasing accordingly. BMS with BWL becomes much more efficient than BMS without BWL, which once again demonstrates the optimal performance that can be achieved by implementing the proposed method.

## 5.2. Variation of calculation parameters

In this section, the results of simulations aimed at studying the effects of variations in calculation parameters will be presented and discussed.

In the SOH-SOC score variation scenario, we changed the weight value for SOH over the entire interval [0, 1], with a step of 0.1. When applying the complete BWL method, a significant variation of the total operating time can be noticed, depending on the weights considered and a maximum value determined by the curve that is formed, can be identified.

In the case of the variation of the  $SOH_{delta}$  parameter, we performed two tests: in the first we increased the threshold value and in the second we decreased it, in order to determine an optimal value. A first conclusion is that the increase of the tolerance threshold for the individual SOH variation compared to the pack average over a value of 2% practically leads to the deactivation of the BWL substitution algorithm, because all the batteries in the pack fall within this wide margin. The reduction of the value of this parameter leads to the increase of the processing time due to the increase of the number of runs of the substitution algorithm. Therefore, in practice it becomes necessary to find an optimal ratio between the processing power used and the performance.

## 5.3. Performance analysis on an external data set

There are several publicly available data sets in the literature, which exemplify the degradation of Li-Ion batteries in various operating scenarios. In the thesis I chose a data set from Oxford University [22], on which to run the proposed method and to assess the degree of improvement.

In order to evaluate the performance of the BWL method on the mentioned data set, the first step was to process the measured current profiles to calculate an average current per cycle. Then we proceeded to model the type of battery used by identifying its parameters ( $K_{co}$ ,  $K_{ex}$ , etc.) based on remaining battery capacity data, measured monthly in the experiment. For this study, a number of 64 batteries were chosen, each with a value of SoH initially randomly generated in the range [0,9; 1]. The values of the  $K_{co}$  and  $K_{ex}$  parameters were also generated in a similar manner. The comparison was made between the BMP optimization variant and the equivalent variant using the BWL method; the results can be observed in the following table.

Table 1 SoH – BWL vs. BMP degradation percent

Cycle no.	SoH degradation in BWL case [%]	SoH degradation in BMP optimization case [%]
343	0,42	0,66
819	0,94	1,35
1431	1,64	2,54

It can be noticed that, starting from the first cycles, the application of the BWL method generates a significantly lower degree of SoH degradation than the reference method. In conclusion, the BWL method obtains better results than the profit maximization algorithm developed by the authors of the studied data set.

## 6. Practical implementation of BMS based on the BWL method

### 6.1. The BMS core and the demo program

This chapter presents the details of the implementation of the core of a BMS based on the BWL method on a series of PC and low-power embedded hardware and software platforms. A comparative analysis will be made in which the advantages and disadvantages of these implementations will be discussed. The demonstration program that was run in this study consisted in applying the BWL method on a series of data that includes complete charging and discharging cycles of the component batteries of a reconfigurable pack, until the termination condition (average SoH <70%).

For an objective comparison between the deployment platforms, we used the same input data and the same source code of the function that implements the core of the BMS. It was initially implemented and verified in the MATLAB environment, then ported to the C language using a semi-automated process. The conclusion of this stage of porting and adapting the demonstration program from MATLAB is that this process is feasible and greatly reduces the evaluation time of the new algorithms, compared to the manual code porting method.

### 6.2. HW and SW platforms for implementation

The characteristics of the chosen platforms cover a wide range of performance variations in terms of execution time, occupied memory and own energy consumed, providing practical information that may be relevant to those who want to implement the proposed method in a functional system.

MATLAB on the Windows x86\_64 platform was used for calculations, simulations and plots required for the practical implementation of the BWL method. In the case of GNU / Linux WSL on the x86\_64 platform, the source code files have been managed using the CMake toolkit and the gcc compilation suite, integrated in the Visual Studio Code editor.

Raspberry Pi (RPI) is a type of Single Board Computer (SBC) but it can also be classified as an embedded system. The operating system is Raspberry Pi OS, a variant of Debian Linux, therefore the same process and the same source code management tools could be reused as in the case of the WSL platform.

In the case of the Nordic nRF ARM Cortex-M4F platform, we used the nRF52840 DK evaluation board and software development kit (SDK) provided by the manufacturer. For the development of the proposed BMS application, we chose the PlatformIO development environment with an Arduino configuration. The implementation of the demonstration program based on the BWL method was done without difficulty, because the *bwl\_sim()* kernel function was executed repeatedly directly from the *loop()* function in Arduino.

The EFM32GG-STK3700 platform is based on the EFM32 Silicon Labs chip, which is one of the most energy efficient microcontrollers available. We used the manufacturer's development environment, Simplicity Studio, and the runtime measurements were performed by directly reading the results received on the PC via the USB-UART adapter integrated on the development board.

### 6.3. Comparative analysis of the obtained results

For the practical evaluation of the performance of a BMS core based on BWL, on the considered platforms, the following 3 metrics were chosen:

1. execution time
2. occupied memory
3. energy consumed.

The following table summarizes the most relevant results of the measurements performed.

Table 2 Results of the BMS performance study

Performance criterion	Platform				
	MATLAB/Windows	GNU/Linux WSL	Raspberry Pi	Nordic nRF	EFM32GG
Execution time [s]	12.5 - 13.5	0.035 - 0.041	0.297 - 0.518	23.17 - 23.19	95.7
Memory RAM/ROM [kB]	302.4 / 29.1	5.5 / 25.0	5.3 / 19.1	5.3 / 21.8	5.4 / 16.8
Energy consumed [J]	210-226	0.59 - 0.69	0.42-0.74	9.47-9.48	6.8

The MATLAB platform was included only as a reference for evaluating the degree of optimization brought by the other implementations in the C language. The GNU / Linux WSL configuration is the most efficient in terms of execution time but it is not an embedded platform. Although the prices of the RPi and Nordic nRF hardware platforms are similar, an optimized BMS can be built cheaper on the Nordic nRF platform than on the RPi, thanks to fewer auxiliary components needed. However, the extensibility and multiple communication options offered by RPi make it the optimum choice for a complex BMS.

## 7. Conclusions and future research

The main contributions of this paper are:

- Research and synthesis of the current state of science in several fields: SOH estimation and prediction, reconfigurable battery packs, wear leveling methods in Flash memories.
- Development and complete description of an innovative method to maximize the service life of rechargeable batteries.
- Development of objective performance criteria for evaluating the effectiveness of the proposed method.
- Analysis of the field of BMS systems with emphasis on management systems for reconfigurable battery packs.
- Detailed design of a management system for reconfigurable battery packs using the BWL method.
- Development of a large number of operating scenarios in order to evaluate the proposed BMS.
- Implementation and adaptation of BMS on 3 embedded reference platforms, with low energy consumption.
- Demonstrating the feasibility of the proposed method by evaluating it on a data set published by Oxford University.
- Dissemination of the doctoral research by publishing 3 scientific papers in ISI indexed journals.

A possible future development direction is to evaluate the impact of the reconfiguration topology on performance, by studying several series-parallel connection configurations. The research should address the impact of the physical implementation of such a system, for example the cumulative resistance of the switches, the possibility of electric arc, etc.

The research can also be continued through practical hardware and software development of a programmable BMS for rechargeable batteries, which would implement the BWL method. This will enable studying aspects related to the practical operation of such a system, through HW / SW optimizations, analysis of implementation costs, etc.

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