Modular battery energy storage system design factors analysis to improve battery-pack reliability

X. Dorronsoro[*], E. Garayalde, U. Iraola and M. Aizpurua

Mondragon Unibertsitatea, Faculty of Engineering, Electronic and Computing Department, Loramendi 4, Mondragon 20500 Gipuzkoa, Spain

ARTICLE INFO

Keywords:
Battery-pack
Lithium-ion battery
Low voltage
Modular batteries
Reliability

ABSTRACT

Traditional battery energy storage systems (BESS) are based on the series/parallel connections of big amounts of cells. However, as the cell to cell imbalances tend to rise over time, the cycle life of the battery-pack is shorter than the life of individual cells. New design proposals focused on modular systems could help to overcome this problem, increasing the access to each cell measurements and management. During the design of a modular battery system many factors influence the lifespan calculation. This work is centred on carrying out a factor importance analysis to identify the most relevant variables and their interactions. The analysis models used to calculate the reliability of the batteries are the state of health (SoH) and the Multi-State System (MSS) analysis with the Universal Generating Function (UGF), while electronic devices reliability is approximated using constant failure rate achieved with FIDES guide. Thus, it is determined numerically that module redundancy, cell capacity, module voltage and their interactions are the most determinant design characteristics.

1. Introduction

The penetration of renewable energy sources into the main electrical grid has dramatically increased in the last two decades. Fluctuations in electricity generation due to the stochastic nature of solar and wind power, together with the need for higher efficiency in the electrical system, make the use of energy storage systems increasingly necessary. To address this challenge, battery energy storage systems (BESS) are considered to be one of the main technologies [1].

Every traditional BESS is based on three main components: the power converter, the battery management system (BMS) and the assembly of cells required to create the battery-pack [2]. When designing the BESS for a specific application, there are certain degrees of freedom regarding the way the cells are connected, which rely upon the designer's criterion. Taking the energy of the battery-pack as a design specification and assuming that a DC/DC converter will adapt the voltage level required by the application, the number of cells connected in series and in parallel is a decision that will need to be addressed.

Most of the BESSs that have been developed until now were designed specifically for one application and in most cases scalability and reusability criteria were not taken into account. These kind of designs are becoming progressively outdated. In some cases, due to the lack of robust design criteria, many accelerated degradation issues were prevented by oversizing [3].

Nowadays, one of the most sought-after features in new designs is modularity. Taking this as a reference, it can be observed that the design of a traditional BESS with a high number of cells in series goes against this concept. This is because the reusability of the design and even the repair or replacement of cells becomes much more challenging in a battery-pack with a large number of cells. Modularity allows to easily customize the design for different voltage, power and energy levels. According to [2], using these new solutions it is possible to avoid problems like power and voltage stress in the power electronic components. While at the same time, it may provide improvements like the possibility to perform active thermal distribution control strategies and active cell/module balancing strategies [4, 5].

In addition to the technical benefits that a modular system can offer, it can also provide greater reliability levels if properly designed. Among other things, greater reliability will provide a longer service life for the entire system. But not only that, if the factors that affect the reliability are known, the BESS can be designed in such a way that the most critical parts can have some redundancy that will allow it to remain operational. All this could be translated into considerable financial savings for the operator of the system.

As mentioned above, the number of cells in series and, consequently, the voltage of the battery-pack, are key factors to take into account. Nevertheless, they are not the only ones to be considered. In order to make the most appropriate battery-pack design, all the parameters that affect the reliability of the system should be determined. Once this set

---

[*] Corresponding author

✉ `E-mail adress: xdorronsoro@mondragon.edu` (X. Dorronsoro)
ORCID(s): `0000-0002-8030-2767` (X. Dorronsoro)

of parameters has been defined, it is necessary to quantify in some way the influence of each one so that the most relevant parameters can be identified. In the same way, this study will also show which of these are negligible and can be discarded from the battery-pack design guidelines. All in all, this research article aims to deepen and demonstrate by quantitative results the relevance of these factors for obtaining reliable designs.

To achieve this reliability results two different calculation methods are available nowadays, the empirical-based approach and the physics of failure method [6]. Although the latter option is the most accurate method it is time consuming because of the complexity of the calculations involved. Therefore, empirical method based reliability estimation system is the chosen option.

Building on the FIDES guide [7, 8] it is possible to set the electronic hardware (power converter + BMS) failure rate (λ). This FIDES guide, according to literature, is assumed to be a suitable method to estimate the electronic components reliability. In the case of individual cells and battery-packs, some recent articles suggest improving this life expectancy estimation combining cells SoH approach [9–13] and MSS reliability analysis with UGF [14, 15]. Using UGF will allow to make each cell's reliability dependant of the corresponding degradation characteristics instead of using fixed failure rate values from the literature. As the whole modular structure reliability analysis is the objective, the 'k out of n' reliability evaluation method is included in the last calculation step [16]. Finally, a factorial analysis is used so as to identify the relevance of each of the parameters of the ultimate reliability designs [17].

To perform this study the paper is organized in three main sections. The research begins by studying the reliability model of each of the components, which is presented in Section 2.1. This is followed by a factorial analysis strategy that is explained using a step by step scheme in Section 2.2. Introduced all the theoretical framework, the obtained results are shown in Section 3. Finally, to sum up the work done, conclusions and future research ideas are presented in Section 4.

2. Methods

2.1. Reliability model of a BESS

In order to evaluate the BESSs' reliability, it is necessary to deeply analyse the failure rate of each of the components. All these items are considered to be independent and not reparable. Once the individual result of both, the cells and the electronic hardware is obtained, the next step is to establish a reliability calculation method for the whole BESS. Figure 1 presents an overall point of view of the steps followed during the reliability analysis.

2.1.1. Cell reliability calculation

With the aim of estimating the individual cells' reliability, it is necessary to monitor the operating conditions and specially the stress factors. To this end, this research works under the assumption that different kinds of measurements (temperature, current and voltage) as well as control strategies (charge equalization) are included in the system. Thus, it is feasible to estimate the SoH of the observed cells.

Table 1
SoH estimation parameters in equation 1 according to [9].

Temp. [ºC]	k_1 [cycle^{-2}]	k_2 [cycle^{-1}]	k_3 [A^{-1}]
25	$8.5 \cdot 10^{-8}$	$2.5 \cdot 10^{-4}$	$2.68 \cdot 10^{-2}$ (≤300) $7.26 \cdot 10^{-2}$ (≤800)
50	$1.6 \cdot 10^{-6}$	$2.9 \cdot 10^{-4}$	$5.2 \cdot 10^{-2}$ (≤300) $6.82 \cdot 10^{-2}$ (≤500)

So as to quantify the SoH in the context of reliability, different examples can be found in the literature. In [10, 11] they develop complex systems that consider the multiphysics of the battery-pack (thermal model and fluid dynamics model) as well as degradation models of the cell, including the stochastic capacity degradation and the dynamic response impedance model. Ah throughput approach analysis is proposed in [13] were SoH is directly calculated by means of semi-empirical capacity fade models, without developing complex and time consuming multiphysics models. In the same way, in [12] they use real Li-ion cell data obtained from the [9] to carry out a SoH calculation. Between the aforementioned articles, due to the simplicity and low computational cost, the research paper [12] has been chosen as the most adequate analysis method. Summarizing, in all these articles, once they obtain the SoH value and considering normal or weibull distributions they use MSS reliability analysis method. Thus, by using UGF [15] it is possible to get the reliability of the cell and the battery-pack.

In accordance with the steps followed in article [12], it is possible to estimate the SoH of the lithium-ion battery, within the range of zero to one, by using the Equation 1

$$SoH = 1 - (\frac{1}{2}k_1N^2 + k_2N) - \frac{k_3}{Q_{max,ini}}i \tag{1}$$

where i is the working current, N is the number of cycles and $Q_{max,ini}$ is the initial nominal capacity of the cells. $k1$, $k2$ and $k3$ are constant values for specified operating conditions, but they are function of the temperature and of the C rate, specified in the Table 1. It may be taken into account that the cell characteristics corresponding to the cylindrical model Sony US18650S with LCO chemistry could not be the optimal solution, however it is assumed to be enough for the methodology and results analysis of this research. Once the procedure to estimate the life expectancy is obtained, it is feasible to continue with the reliability analysis of the MSS.

A MSS operation can be summarized on a finite amount of performance rates [15]. Since every operating cell's SoH is variable in a BESS (due to inhomogeneities between each other), it is possible to distinguish different operation levels; by discretising the degradation process. To that end, the normal distribution theory of Equation 2 is applied in order

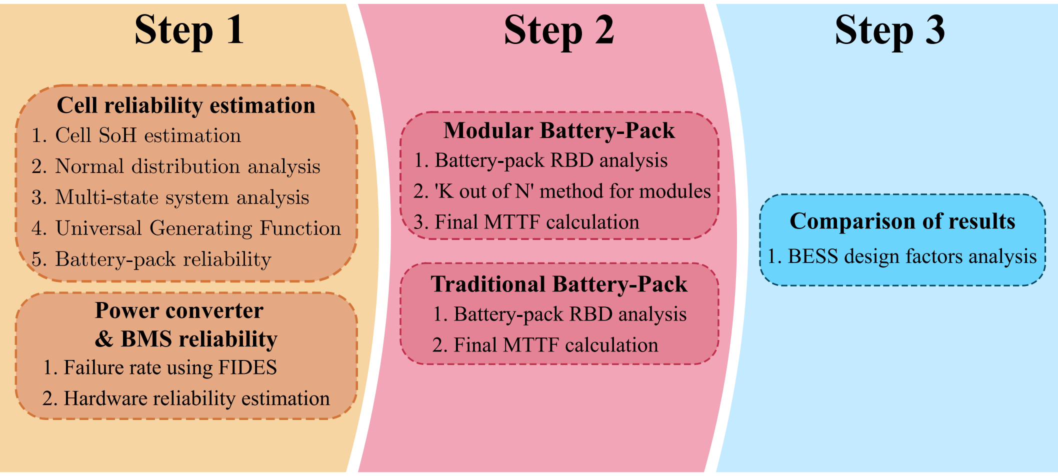

Figure 1: BESS reliability analysis summary.

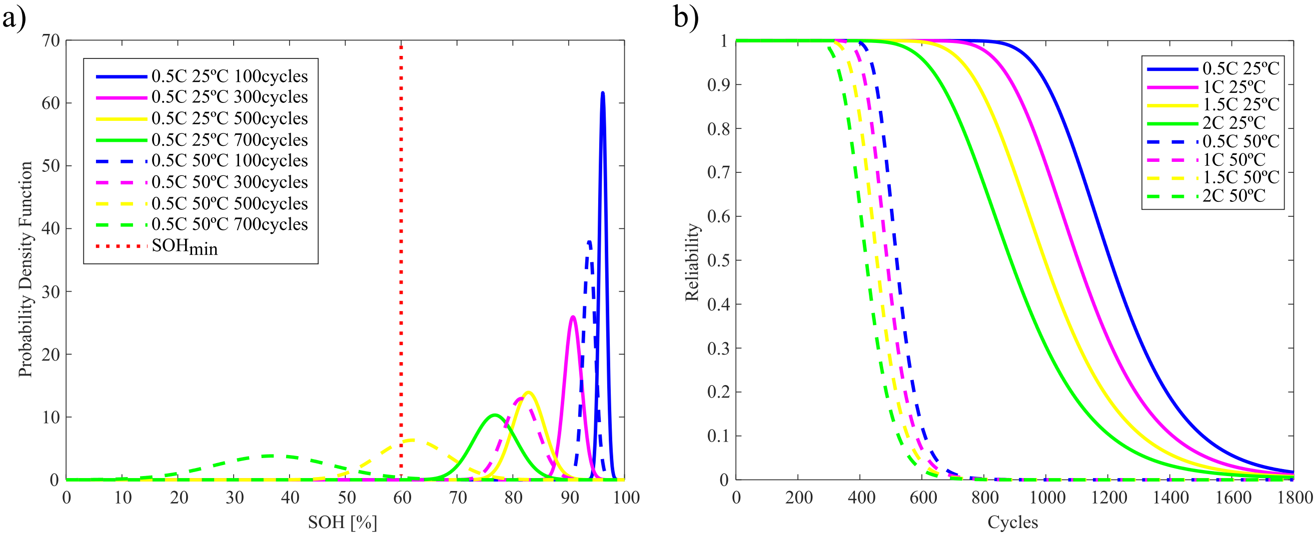

Figure 2: Cell lifespan evaluation example a) SoH probability density function under different operating conditions b) cell reliability estimation during the operating time period.

to calculate the probability of the SoH being within different performance ranges. This analysis enables reliability calculation for different cell degradation levels. For this research the mean value (μ) is the SoH value estimated using the Equation 1, while the range of distribution (x) for which the probability density function has to be applied is limited to a fixed range, from the lowest SoH limit of 60% to the maximum of 100%.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{2}$$

As stated in [10], the first step is to estimate the deviation σ following the Equation 3. After calculating σ, Equation 2 is used to get the probability distribution. Attending to the resulting data, Figure 2a shows the probability distribution for the calculation of a current of 0.5C, under different temperatures and cycles influence, by using the aforementioned SoH estimation method.

$$\sigma = \frac{1-\mu}{6} = \frac{1}{6}\left[\left(\frac{1}{2}k_1 N^2 + k_2 N\right) + \frac{k_3}{Q_{max,ini}} i\right] \tag{3}$$

After obtaining the probability values using the normal distribution function, it is possible to continue with the reliability calculation resorting to UGF. This method aims to discretise the performance of the cells and demands to express the u-function ($u(z)$) of each cell in line with Equation 4. By means of the u-function it is feasible to distribute the probability of the cells SoH for being into a certain range (z^k, being K the number of ranges from 0 to 100).

$$u(z) = \sum_{k=1}^{K} p(k) z^k \tag{4}$$

Analysed the u-function of each cell, the next step prior to the estimation of the final reliability is to build the operator that represents the battery-pack. The $\underset{f_{\text{SoH}}}{\otimes}$ presented in Equation 5, and detailed in Equation 6, determines how to carry out the mathematical operation required, depending on the cell's parallel (I: amount of cells in parallel) and series (J: amount of cells in series) configuration.

$$U(z) = \sum_{j=1}^{J} \sum_{i=1}^{I} \underset{f_{\text{SoH}}}{\otimes} \left(u_{(i,j)}(z) \right) \tag{5}$$

$$\underset{f_{\text{SoH}}}{\otimes} = \begin{cases} \min\left\{g_1, \dots, g_J\right\}, & \text{series} \\ \max\left\{g_1, \dots, g_I\right\}, & \text{parallel} \end{cases} \tag{6}$$

Once the probability values p(k) corresponding to the U(z) of the battery-pack are calculated, it is possible to finish with the MSS reliability analysis. To that end, the system is divided in two states: working state (SoH over 60%) and failure state. Following the Equation 7 and considering the previously mentioned characteristics reliability is determined. For instance, the Figure 2b shows different reliability curves for a single cell under different cycling conditions.

$$R_{BP} = P\left\{k \geq SoH_{min}\right\} = \sum_{k \geq SoH_{min}} p(k) \tag{7}$$

2.1.2. Electronic hardware reliability calculation

For a better alignment between the reliability of the modules and the behaviour of a real design, the inclusion of power electronic converter, as well as BMS influences, is suggested. Within this reliability-centred framework, the most recent empirical based methods are the FIDES guide and the RIAC-217PLUS [6]. The comparison that has been performed in [8] shows that, although there are some admissible deviations to field data, using both methods remain acceptable. For this article FIDES guide has been selected due to the documentation availability. The reason why the most extended reliability calculation tool MIL-Hdbk-217 is not used, is simply because it is beginning to be outdated (last update: 1995) for new technologies [6].

This recent FIDES guide enables the calculation of new generation electronic technology's failure probability λ more accurately. This new development presents some different methods for estimating the lifespan of electronic components. Thus, usefulness of each reliability estimation procedure relies on the available information. In this article, only the converter's working characteristics are considered, specifically, the voltage amplification range and the power efficiencies presented at [18].

Since a detailed electronic hardware design process is omitted, the calculation approach that fits best the research requirements is the 'family count' method. As described in [19], this method allows doing a reliability estimation during the earliest design phases with the minimum information. The definition of the operating profile that would represent the application conditions is enough to achieve the failure rate value. In view hereof, the Table 2 presents the official template along with the data required by the FIDES to estimate the reliability.

The failure rate (λ) obtained with this guide is 8767.1 FIT (number of failures that can be expected in one billion device-hours of operation). Then, based on the classical reliability approach of Equation 8 with exponential distribution, it is feasible to estimate the electronic components reliability (R_{conv}). Once the real electronic hardware is developed, the value will not remain equal to this initial estimation. However, as cells are the most relevant items, this initial approximation should be enough to analyse the advantages and disadvantages of BESS [20, 21].

$$R_{conv}(t) = e^{-\lambda t} \tag{8}$$

2.1.3. Single battery module reliability calculation

Having approximated the reliability of the batteries and the electronic hardware, the last step is to delve into the methodology employed to analyze the complete system. Since the MSS performance rate definition of electronic hardware would need a deeper analysis, a new method is required in order to meet this objective.

To face up this new scenario, different reliability strategies (static or dynamic) are available nowadays, for instance the Petri Nets (PN) [22] or the Monte Carlo Simulation (MCS) method [23]. Between the available options the classical reliability block diagram (RBD) technique has been chosen [24] due to the fact that allows operating with series, parallel and any other complex system structure, including the redundancy factor and being a relatively simple model. In this regard, as each battery-pack is connected in series with the electronic hardware, following the RBD theory, the final reliability of single modules (R_{module}) can be achieved by using the Equation 9.

$$R_{module} = R_{BP} R_{conv} \tag{9}$$

The last step to obtain the reliability of modular BESS is to consider the characteristic 'variable configuration': single string series-parallel (S-P) or parallel-series (P-S) systems can be substituted by complex modular matrix structures that demand a more specific analysis method. This kind of structures depending on the design characteristics may enable the option to operate by means of redundant configurations. For this research, the failure state is assumed to be when the converter is not able operate within the full

Table 2
FIDES guide reliability calculation required information.

Standard life profile			Temperature	Temperature cycling			
Phase name	On / Off	Calendar time	Ambient temperature	Δt(°C)	Cycle duration	Numbre cycles	Maximum cycling temperature
PH1	ON	182 h	25,00 °C	40,00 °C	1 h	182	65,00 °C
PH2	OFF	4.198 h	25,00 °C	0,00 °C	23 h	183	25,00 °C
PH3	ON	182 h	25,00 °C	40,00 °C	1 h	182	65,00 °C
PH4	OFF	4.198 h	25,00 °C	0,00 °C	23 h	183	25,00 °C

Standard life profile	Humidity	Mechanical	Chemical			
Phase name	Relative humidity	Random vibrations	Saline pollution	Environmental pollution	Application pollution	Protection level
PH1	50%	0,10 Grms	Low	Moderate	Low	Non hermetic
PH2	50%	0,10 Grms	Low	Moderate	Low	Non hermetic
PH3	50%	0,10 Grms	Low	Moderate	Low	Non hermetic
PH4	50%	0,10 Grms	Low	Moderate	Low	Non hermetic

demanded output voltage range or it suffers any kind of limitation regarding the operating power. Thus, 'k out of n: G System' has been chosen as an alternative to continue with this research. As stated by the theory presented in [16], although there are more accurate but much more complex options, it is capable of approaching in a relatively simple way static reliability values for these battery system. This method is grounded on identical and independent items that share the same reliability. Such technique is employed to analyse systems where at least k out of n items are operating. The Equation 10, in which p represents the reliability R_{conv} and q stands for the unreliability, enables to estimate the full system's reliability (R).

$$R(k,n) = \sum_{i=k}^{n} \binom{n}{i} p^i q^{n-i} \tag{10}$$

n is the total amount of total series/parallel modules and k is the amount of series/parallel redundant modules. This k value is dependant on the variable design factors presented in Table 3, and is obtained as follows:

- No series and no parallel redundancy for any module configuration: k is equal to zero in all cases.
- Only series redundancy for any module configuration: on the one hand there is a system to module maximum voltage limitation and, on the other hand, there is a the system to module maximum power limitation. The k value is defined by the most restrictive option.
- Only parallel redundancy for any module configuration: the k value is defined by the relation of the operating C rate and the maximum C rate of the modules.
- Parallel and series redundancy for two different module configurations
  - P-S configuration: initially parallel modules k redundancy value is defined with the operating C rate and the maximum C rate of all the modules. Then, the rest of the redundant modules are used to include series redundancy considering the voltage ratios and power limitations as mentioned in the second point.
  - S-P configuration: initially series redundancy is established. On the one hand there is a system vs module maximum voltage limitation and on the other hand there is the system and modules maximum power limitation. The k value is defined by the most restrictive principle. The rest of the redundant modules are used for parallel redundancy using the C rate limitation as mentioned in the third point.

However, doing an analysis with many variables results in a large number of reliability curves (similar to the Figure 2b but with different shapes). In these cases, it is challenging to distinguish the advantages and disadvantages of each result. To fix this problem, it is key to calculate the Mean Time To Failure (MTTF) with Equation 11 [14]. Therefore cell reliability value is estimated taking into account the SoH limit of 60% and electronic reliability is value is approached using data from table 2. Finally, after applying the RBD and 'k out of n' techniques, the MTTF value enables estimating an average reliability during the predefined life expectancy period (T,is the time corresponding to the maximum amount of cycles).

$$\mathrm{MTTF} = \int_0^T R(t)dt \tag{11}$$

2.2. Factor importance analysis methodology

With the main components of the reliability estimation method defined, the next step is to focus on the whole BESS

Table 3
Fixed values and variable factors for the reliability analysis.

Fixed values		Analyzed values	
Factor	Value	Factor	Value
System voltage	1500 V	Modules configuration (Conf)	P-S
			S-P
System energy	48 kWh	Series redundancy (Rs)	No
			Yes
Cell Voltage	3.2 V	Parallel redundancy (Rp)	No
			Yes
Cell C rate$_{max}$	2 C	Cell capacity (Ah)	Low (5 Ah)
			High (40 Ah)
Cell SoH$_{min}$	60%	Modules voltage (V)	Low (48 V)
			High (500 V)
Temp.	25 °C	Voltage Amplification (Amp)	Low ([2 1.5])
λ converter	8767.1 FIT		High([30 3])
Single cell string			

analysis. To that end, different variable factors have to be defined. Nevertheless, it should be noticed that there is no previous knowledge of which of these factors are going to improve the final design. Having that said, this article aims to describe how each variable influences the reliability result in order to establish a criterion for the design process of battery-packs.

Based on the numerical reliability analysis method of the Section 2.1, an iterative process able to estimate the MTTF for each design characteristic combination is developed. Among the different importance analysis methods (for instance, Birnbaum and Failure Criteria) factorial regression analysis has been chosen [17]. This method allows to quantify the relevance of each design factor of the battery-pack. The Figure 3 shows the different DC architectures available for BESS configurations: traditional battery-pack, P-S modular-pack and S-P modular-pack. Nevertheless, in the design process there are more factors that can vary, all of them presented in Table 3.

In order to fulfill this combinatorial analysis the following algorithm has been developed, divided in four main steps:

- Step1: initialization of the fixed values and variable factors. Along with the creation of the factorial analysis matrix.
- Step2: define the number of iterations that are needed to analyse each of the design factor of a BESS.
- Step3: estimation of SoH, cell reliability, module RBD, redundancy levels, and finally, the MTTF of the whole system.

Table 4
Top MTTF results at 0.5 C for modular BESSs.

Conf	Rs	Rp	Ah	V	Amp	MTTF
1-2	1-2	2	2	1	2	0,5528
1-2	1-2	2	1	1	2	0,5510
1	1-2	2	1	1	1	0,5256
1	2	2	2	1	1	0,5180
1	1	2	2	1	1	0,4897
1-2	1-2	2	2	2	2	0,4891

Table 5
Top MTTF results at 1.5 C for modular BESSs.

Conf	Rs	Rp	Ah	V	Amp	MTTF
1-2	1-2	2	2	1	2	0,3763
1-2	1-2	2	1	1	2	0,3739
1	1-2	2	1	1	1	0,3467
1	2	2	2	1	1	0,3385
1-2	1-2	2	1	2	2	0,3278
2	2	2	1	1	1	0,3255

- Step4: once the results are obtained, it is necessary to proceed performing a factorial regression, so as to determine each design factor's relevance.

This scheme also enables to approximate the reliability value for a traditional BESS built with a single cell group and a single power converter. However, some initial considerations vary in this conventional structure: cells' matrix configuration, no modular configurations and no modular redundancy characteristic.

3. Results

After analysing the design characteristics and the reliability estimation methodology in Sections 2.1 and 2.2, this Section presents the results obtained. To that end, this research takes into account different C rates: 0.5 C as an energy application and 1.5 C as a power application.

First, the quantitative MTTF results are displayed. Yet, in order to avoid presenting excessive data related to each factors' combination, only the most significant designs are shown. Tables 4 and 5 contain the modular BESSs MTTF values, while Tables 6 and 7 show the reliability results that correspond to traditional BESSs. According to this results, the reliability of modular battery-packs is up to 20.24% over the conventional BESSs for energy applications. With regards to power applications, the modular configurations' reliability is up to 16.21% higher than the MTTF corresponding to the conventional BESS.

Secondly, after reviewing the improvement that the modular BESS involves, it is necessary to focus on the considered initial design's details. In this regard, the relevance of each factor and their interactions are to be determined by resorting to a factorial analysis. The Figure 4 shows the Pareto charts at 0.5 C and 1.5 C. Every standardized effect having a value

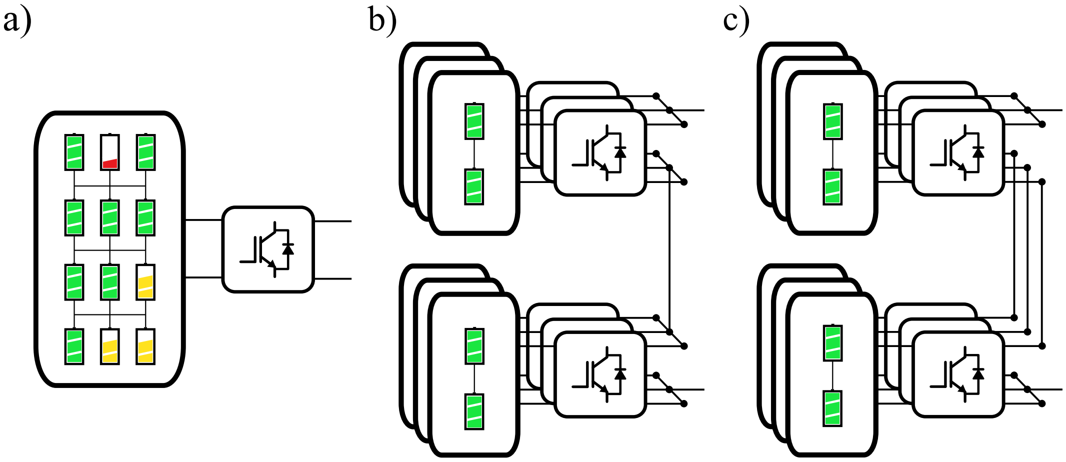

Figure 3: BESS configurations for DC a system a) conventional BP structure b) P-S modular structure c) S-P modular structure.

Table 6
Top MTTF results at 0.5 C for conventional BESSs.

Ah	V	Amp	MTTF
2	2	1-2	0,4477
2	1	1-2	0,4445
1	2	1-2	0,4192
1	1	1-2	0,4189

Table 7
Top MTTF results at 1.5 C for conventional BESSs.

Ah	V	Amp	MTTF
2	2	1-2	0,3213
2	1	1-2	0,3178
1	2	1-2	0,2905
1	1	1-2	0,2902

above the limit of 2.07 is considered to have an influence in the design reliability. However, between all the factors and interactions it is evident that some of them have a major weight. For both C rates, these are the top five aspects to take into consideration:

- Parallel redundancy.
- Interaction between parallel redundancy and module voltage.
- Interaction between parallel redundancy and cell capacity.
- Cell capacity.
- Module voltage.

In addition to the Pareto charts, the interaction behaviour of the different factors presented in Figure 5 is required. The graphs show that focusing on low voltage modules and low capacity cells is relevant, but focusing on parallel redundancy is mandatory. Although both applications are operating at different C rates, the design factors' criterion remains the same.

In summary, three main factors have the greatest impact in the reliability upgrade: parallel redundancy, low voltage and cell capacity. For each modular BESS based application, the impact has been quantified as follows:

- Energy application: The inclusion of modular parallel redundancy increases the reliability up to 21.78%. In the case of low voltage modules, the MTTF is 11.52% higher than with high voltage modules. Regarding the cell capacity, high levels of Ah reducing the amount of cells becomes a crucial factor when no modular redundancy is found. Otherwise, the cell capacity is not such a decisive factor.
- Power application: The inclusion of modular parallel redundancy increases the reliability up to 14.03%. In the case of low voltage modules, the MTTF is 12.89% higher than with high voltage modules. With regards to the cell capacity, high levels of Ah reducing the amount of cells becomes a crucial factor when no modular redundancy is found. Otherwise, the cell capacity is not such a decisive factor.

4. Conclusions

In view of the difficulty for defining the design factors of a BESS, a reliability analysis method including a factorial regression has been developed. By using this strategy, a factor relevance research has been carried out for conventional and modular battery-packs, obtaining the following conclusions:

- Creating big size battery-packs has been the traditional solution for BESSs. With the results obtained in this research, it is numerically demonstrated that new technological solutions towards more reliable modular BESSs are mandatory. In parallel, this improvement may enable the incorporation of new control strategies

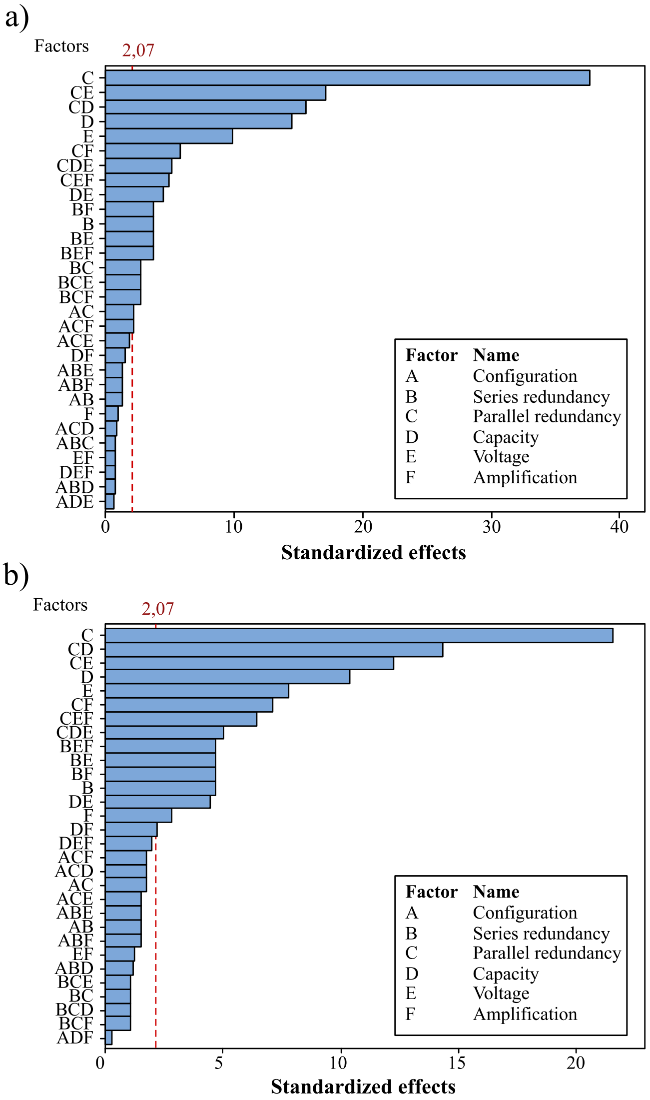

Figure 4: Pareto charts to determine factors and interactions relevance a) at 0.5 C b) at 1.5 C.

and new replacement systems of damaged battery-packs. This will contribute to maintain a consistency of the whole system, which should help extending the lifespan.

- The main factors and interactions that have an influence over the BESS reliability are the parallel redundancy, the cell capacity and the module voltage as well as their interactions. The best combination of this factors is to increase the redundancy, while reducing not only the capacity of the cells, but also the modules voltage. This data evidences the determining nature of these three characteristics in the optimization of the final result.
- As expected, by comparing the energy application and power application, becomes clear that lower C rates imply a larger lifespan due to the higher reliability results obtained. In relation to power applications, higher C rates result in the BESS faster degradation process. Nevertheless, there is not a direct correlation between the operating current and the MTTF of the BESS. Therefore, the reduction by half of the power system's current, does not imply that the reliability will increase twice.

In sum, although this research presents interesting quantitative results, further analysis is required in order to obtain more accurate reliability estimations. In this regard, the inclusion of more detailed performance data, related not only to the cell multiphysics but also to the electronic hardware, is recommended. Finally, it is worth mentioning that the methodology employed in this research can be replicated in AC BESS applications with the aim of identifying the most relevant factors for battery reliability analysis.

5. Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] G. Zubi, R. Dufo-López, M. Carvalho, G. Pasaoglu, The lithium-ion battery: State of the art and future perspectives, Renewable and Sustainable Energy Reviews 89 (2018) 292–308. `doi:https://doi.org/10.1016/j.rser.2018.03.002`.

[2] Y. Li, Y. Han, Evaluation of a module-integrated distributed battery energy storage system, in: 2015 IEEE Energy Conversion Congress and Exposition (ECCE), 2015, pp. 1351–1358. `doi:10.1109/ECCE.2015.7309850`.

[3] T. Terlouw, T. AlSkaif, C. Bauer, W. van Sark, Multi-objective optimization of energy arbitrage in community energy storage systems using different battery technologies, Applied Energy 239 (2019) 356–372. `doi:https://doi.org/10.1016/j.apenergy.2019.01.227`.

[4] M. Quraan, T. Yeo, P. Tricoli, Design and control of modular multilevel converters for battery electric vehicles, IEEE Transactions on Power Electronics 31 (1) (2016) 507–517. `doi:10.1109/TPEL.2015.2408435`.

[5] A. M. Divakaran, D. Hamilton, K. N. Manjunatha, M. Minakshi, Design, development and thermal analysis of reusable li-ion battery module for future mobile and stationary applications, Energies 13 (6) (2020). `doi:10.3390/en13061477`.

[6] V. Kumar, L. K. Singh, A. K. Tripathi, Reliability prediction methods for electronic devices: A state-of-the-art review, IETE Technical Review 0 (0) (2020) 1–11. `doi:https://doi.org/10.1080/02564602.2020.1843552`.

[7] F. Guide, et al., Reliability methodology for electronic systems, FIDES group 465 (2009).

[8] M. Held, K. Fritz, Comparison and evaluation of newest failure rate prediction models: Fides and riac 217plus, Microelectronics Reliability 49 (9) (2009) 967–971, 20th European Symposium on the Reliability of Electron Devices, Failure Physics and Analysis. `doi:https://doi.org/10.1016/j.microrel.2009.07.031`.

[9] P. Ramadass, B. Haran, R. White, B. N. Popov, Mathematical modeling of the capacity fade of li-ion cells, Journal of Power Sources 123 (2) (2003) 230–240. `doi:https://doi.org/10.1016/S0378-7753(03)00531-7`.

[10] Q. Xia, Z. Wang, Y. Ren, B. Sun, D. Yang, Q. Feng, A reliability design method for a lithium-ion battery pack considering the thermal disequilibrium in electric vehicles, Journal of Power Sources 386 (2018) 10–20. `doi:https://doi.org/10.1016/j.jpowsour.2018.03.036`.

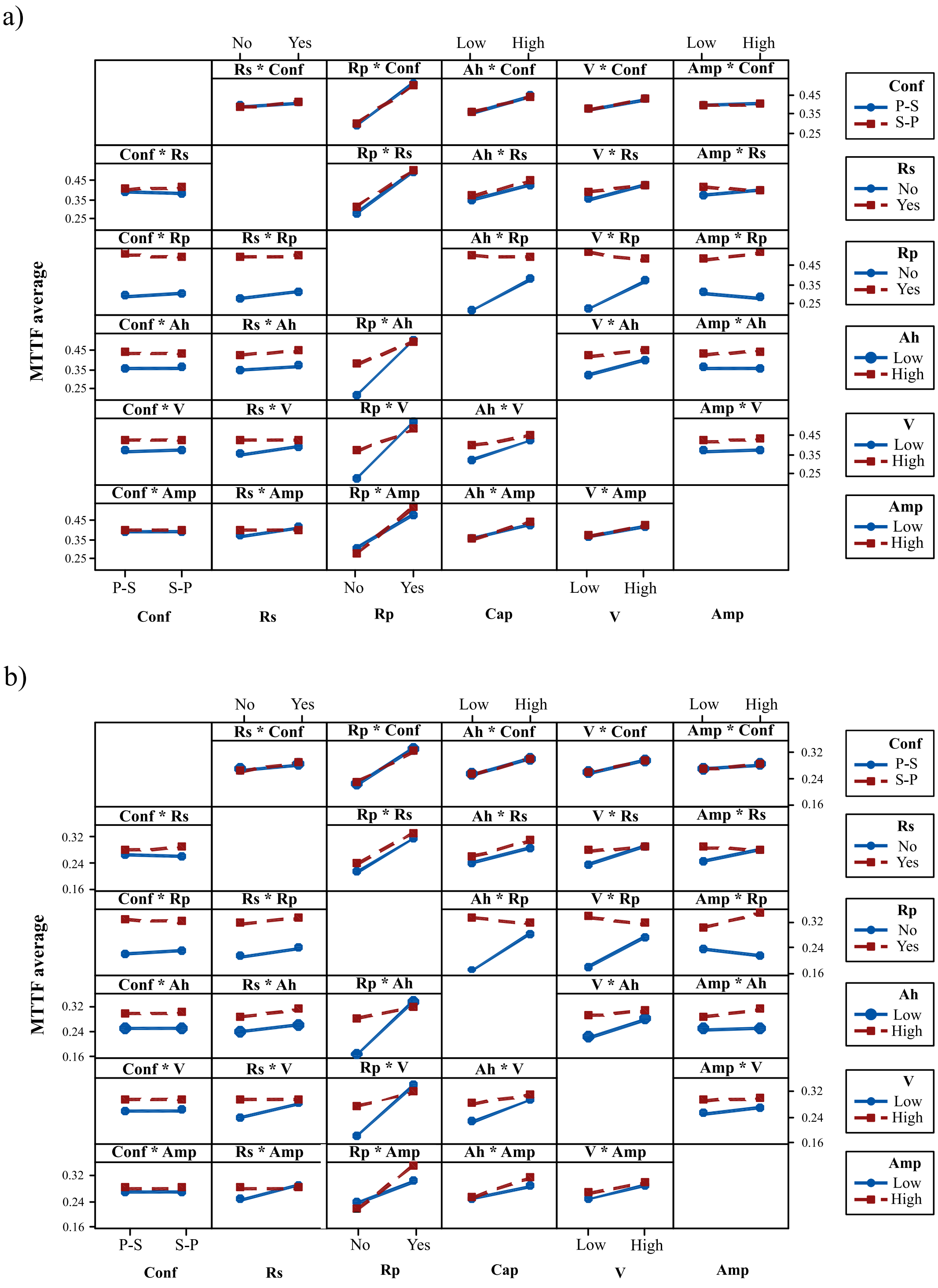

Figure 5: Factors interactions a) at 0.5C b) at 1.5C.

[11] Q. Xia, Z. Wang, Y. Ren, L. Tao, C. Lu, J. Tian, D. Hu, Y. Wang, Y. Su, J. Chong, H. Jin, Y. Lin, A modified reliability model for lithium-ion battery packs based on the stochastic capacity degradation and dynamic response impedance, Journal of Power Sources 423 (2019) 40–51. `doi:https://doi.org/10.1016/j.jpowsour.2019.03.042`.

[12] Z. Liu, C. Tan, F. Leng, A reliability-based design concept for lithium-ion battery pack in electric vehicles, Reliability Engineering & System Safety 134 (2015) 169–177. `doi:https://doi.org/10.1016/j.ress.2014.10.010`.

[13] M. Liu, W. Li, C. Wang, M. P. Polis, L. Y. Wang, J. Li, Reliability evaluation of large scale battery energy storage systems, IEEE Transactions on Smart Grid 8 (6) (2017) 2733–2743. `doi:10.1109/TSG.2016.2536688`.

[14] A. Lisnianski, I. Frenkel, L. Khvatskin, et al., Modern Dynamic Reliability Analysis for Multi-state Systems, Springer, 2021.

[15] G. Levitin, et al., The universal generating function in reliability analysis and optimization, Vol. 6, Springer, 2005.

[16] M. J. Zuo, J. Huang, W. Kuo, Multi-state k-out-of-n systems, in: Handbook of reliability engineering, Springer, London, 2003, pp. 3–17. `doi:https://doi.org/10.1007/1-85233-841-5_1`.

[17] J. Antony, Design of Experiments for Engineers and Scientists, second edition Edition, Elsevier, Oxford, 2014. `doi:https://doi.org/10.1016/B978-0-08-099417-8.00010-9`.

[18] K. L. Jorgensen, M. C. Mira, Z. Zhang, M. A. E. Andersen, Review of high efficiency bidirectional dc-dc topologies with high voltage gain, in: 2017 52nd International Universities Power Engineering Conference (UPEC), 2017, pp. 1–6. `doi:10.1109/UPEC.2017.8231916`.

[19] A. France, Eurocopter, N. Electronics, M. missile systems, T. S. A. SA, T. Avionics, T. C. S. SAS, T. U. Systems, Fides guide 2009 edition a-reliability methodology for electronic systems, FIDES Group and others (2009).

[20] X. Shu, W. Yang, Y. Guo, K. Wei, B. Qin, G. Zhu, A reliability study of electric vehicle battery from the perspective of power supply system, Journal of Power Sources 451 (2020) 227805. `doi:https://doi.org/10.1016/j.jpowsour.2020.227805`.

[21] H. Liu, M. Panteli, A reliability analysis and comparison of battery energy storage systems, in: 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), 2019, pp. 1–5. `doi:10.1109/ISGTEurope.2019.8905658`.

[22] J.-P. Signoret, Y. Dutuit, P.-J. Cacheux, C. Folleau, S. Collas, P. Thomas, Make your petri nets understandable: Reliability block diagrams driven petri nets, Reliability Engineering & System Safety 113 (2013) 61–75. `doi:https://doi.org/10.1016/j.ress.2012.12.008`.

[23] E. Zio, Springer Series in Reliability Engineering, Springer, London, 2013. `doi:https://doi.org/10.1007/978-1-4471-4588-2`.

[24] A. Birolini, Reliability engineering, 8th Edition, Springer, Berlin, Heidelberg, 2017. `doi:https://doi.org/10.1007/978-3-662-54209-5`.