AC Battery: Modular Layout with Cell-level Degradation Control

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Acknowledgments

This work was supported in part by "Agencia Nacional Investigacion y Desarrollo" (ANID) under grants: ANID/FONDECYT de Iniciación/11220989, ANID/FONDECYT de Iniciación/11221230 and ANID/PAI/PAI7719002.

Keywords

≪Battery≫, ≪Consensus-based cooperative control≫, ≪Degradation≫, ≪Energy storage≫, ≪Lifetime≫, ≪Modular Multilevel Converters≫

Abstract

This paper proposes a three-phase AC battery based on the modular multilevel converter (M2C). The AC battery concept allows plug-and-play combinatorial integration of diverse battery cells with different characteristics such as nominal voltage, state of charge (*SoC*), and degradation levels. The resulting modular and reconfigurable battery pack can cost-effectively cover various applications, from electrified vehicles to stationary storage. To this end, in each sub-module (*SM*) of the M2C, battery cells (or battery modules composed of one or more battery cells) are connected to a single capacitor, thus enabling a cell-to-cell battery integration and control. In this scenario, the traditional battery management system (BMS) can be replaced by control schemes at the converter level, aiming to equalise critical parameters associated with battery cells (or battery modules). In this context, the degradation level of battery cells integrated by the proposed AC battery is a critical parameter to be considered. Indeed, it is likely that the integrated battery cells by the AC battery have different degradation levels. Therefore, methods for managing their degradation state are required to equalise the lifespan of battery cells within the AC battery. Based on that, this paper proposes a consensus-based distributed control scheme to manage the degradation process of battery cells (or battery modules composed of one or more battery cells) within the AC battery. Simulation results corroborate the effectiveness of the proposal.

Introduction

In recent years, the use of electric vehicles (EVs) has increased worldwide. This has promoted policies in several countries to adopt environment-friendly transport means, targeting the reduction of greenhouse gases. Recently, some European countries have announced that fossil fuel-based vehicles will be forbidden in only a few years. Thus, the demand for EVs will continue to increase in the coming years [1]. It is noteworthy that a critical component of EVs is the battery energy storage system (BESS). For electromobility applications, a common practice is to use the BESS until its capacity reaches approximately 80%

of its nominal value. After that, the current recommendation is that the BESS is discarded and replaced by a new one. This situation generates opportunities and challenges for efficient and novel solutions that could reuse degraded BESSs as second-life battery systems in smart grids, modern power systems, or less demanding electromobility applications.

The integration of second-life batteries has several challenges as batteries may have different manufacturers, chemistry, voltage, capacity, degradation levels, lifespan, etc. [2]. In this sense, the modular multilevel converter (M2C) has been proposed as a prominent solution that meets all the requirements needed to integrate heterogeneous BESS coming from EVs [3, 4, 5, 6]. Indeed, the M2C allows fulfilling crucial tasks such as (i) distributing battery cells (or battery modules composed of one or more battery cells) on its sub-modules (*SMs*), providing modularity for battery integration, (ii) equalising the state of charge (*SoC*) of battery cells (or battery modules) placed on the M2C *SMs* thanks to the circulating currents, and (iii) lifetime prolongation of battery cells by using suitable modulation techniques and/or proper control of their usage policies [7]. Indeed, in [8, 9, 10], it is argued that pulsed charging/discharging (which is an intrinsic M2C property) can prolong the battery life. In addition, in [7], it is demonstrated that the degradation and lifespan of BESS can be managed, among other criteria, through the operational policies for charging and discharging the battery. In particular, the *SoC* range is constrained to pre-defined ranges during the discharging process. For instance, the degradation of a battery discharged between 100% and 0% of *SoC* is much higher than the same battery being discharged, with an operational policy limiting the *SoC* between 100% and 75% (see [7] for more information).

The use of the M2C for integrating second-life batteries has been proposed in [3, 4, 5, 6]. These references show that the M2C allows a modular integration of battery cells coming from EV applications. Also, control schemes for regulating the *SoC* of batteries placed on the M2C *SMs* were proposed, showing promising results. However, these research efforts have the following drawbacks: (i) they do not provide modularity in terms of computational burden for the M2C control system, as they are based on a centralised control scheme (where a central controller manages the whole system), and (ii) they do not consider active degradation control of the battery cells (or battery modules composed of one or more battery cells) integrated by the M2C.

Based on the research gaps discussed above, this paper proposes the AC battery concept based on the M2C shown in Fig. 1. This topology enables the integration of battery cells on the *SMs* of the M2C. It uses local controllers (*LCs*) placed on *SMs* to implement a distributed control architecture, providing modularity in both battery cells integration and computing capacity required to implement the control system of the proposed AC battery. In addition, it is demonstrated that the degradation level of battery cells within the AC battery can be controlled using a proposed consensus-based distributed control scheme augmented by a degradation management system (DMS). Note that the DMS generates control actions (*dms* signals in Fig. 2) for the proposed consensus algorithm. Additionally, the DMS should be implemented in the cloud to avoid the need for placing control platforms with high computational capabilities in the M2C.

Control Architecture of the Proposed AC Battery

Fig. 2 shows a generic cluster of *N SMs* that comprises the M2C-based AC battery. As observed (on the left), battery cells with different characteristics can be integrated into the cluster through the *SMs*. In each *SM*, an *LC* is placed, which is in charge of driving the respective semiconductor devices and calculating the main operational parameters of the battery cell (or battery modules composed of one or more battery cells) connected to the *SM* (e.g., degradation level, temperature, cycle number). Then, this local information is exchanged with neighbour *LCs* via a distributed communication network (see Fig. 2), enabling the implementation of consensus-based distributed control schemes to regulate one or more parameters of battery cells. As shown in Fig. 2, the AC battery concept allows for integrating battery cells (or battery modules) with different characteristics and specifications. Indeed, each *SM* may be using a battery cell or a battery module with unequal states of charge (*SoCs*), power ratings, and degradation levels. Focusing on the latter, it is noteworthy that the degradation level of the entire AC battery is often determined by the most degraded battery cell (or battery modules) that composes it. In this regard, it is

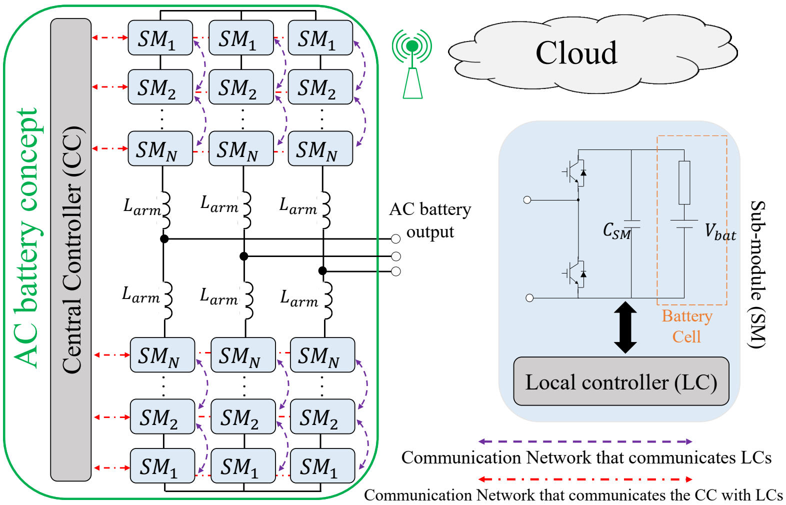


Fig. 1: Proposed modular layout for integrating second-life battery cells (and/or battery modules).

paramount to develop control schemes to manage the degradation that each battery cell/module undergoes, thus improving the lifespan of the entire AC battery. To the authors' best knowledge, this is the first work that proposes the integration of battery cells in a modular layout with cell-level degradation control. In this sense, Fig. 2 shows the proposed AC battery system from where it is possible to distinguish three main points: (i) a central controller (CC), (ii) local controllers (*LCs*) operating in a consensus-based distributed control architecture, and (iii) the cloud, where a degradation management system (DMS) is being run. It must be highlighted that the CC performs the power control of the entire AC battery. In contrast, *LCs* regulate the degradation level of the battery cells (or battery modules) within the AC battery. This is done by the proposed consensus algorithm introduced in the next section. Finally, the DMS aims to manage the M2C to achieve battery-cell-degradation control by generating control actions for the *LCs* to accomplish that control objective. In this sense, it should be pointed out that the DMS is similar to the well-known battery management system (BMS), widely used in battery systems, but in this case, the DMS is tailored for battery degradation. In particular, the DMS is in charge of generating operational policies for charging and discharging each battery cell (in terms of *DoD*) within the AC battery to regulate their degradation levels. In this paper, point (ii) is addressed: it is discussed in the next section. The DMC mentioned in (iii) is ongoing research and will be addressed in future publications.

Proposed Distributed Control Scheme for Degradation Control

Fig. 3 illustrates the proposed control scheme implemented on the ith *LC* (for the rest of the *LCs*, the procedure is analogous). The main aspects of the implementation are discussed below.

Degradation model

Battery degradation is the process in which capacity fades over time. It is also characterised by an increase of the internal impedance, which may dangerously increase operation temperature, eventually making a battery replacement necessary. Battery degradation depends on many factors such as current rate, temperature, number of cycles and their depths of discharge (*DoDs*) [7]. In particular, the *DoD* has an enormous influence on battery lifespan [11, 12, 13]: deep discharges reduce battery lifetimes. Because of this, battery degradation can be indirectly controlled by regulating the *DoD*. In particular, in this paper, we focus on reducing the *DoD*-related degradation by regulating the discharging policies on battery cells [7] (or battery modules composed of one or more battery cells).

To properly analyse and reduce the *DoD*-related degradation, a model that relates the *DoD* policies of the battery cells with their long term degradation is needed. In this work, a simplified version of the model of [7] is used. A cycle is defined as the period of time since a discharging period starts until a charging period ends (Fig. 4 shows the cycle considered in this work). Let $Q_i(k)$ be the capacity of battery cell ith

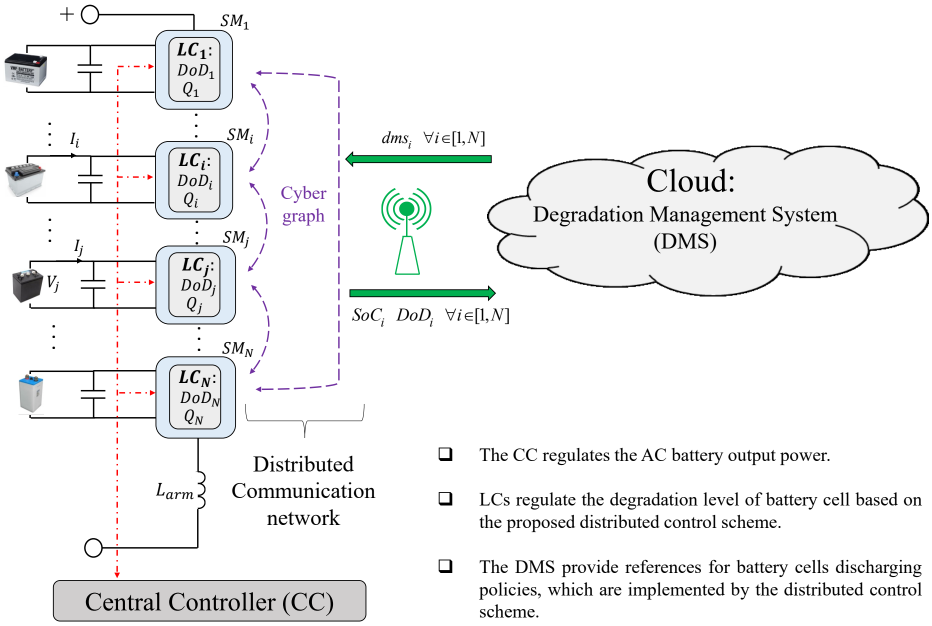


Fig. 2: Proposed control architecture for regulating the degradation level of battery cells that composed the AC battery. (One cluster of the M2C is shown)

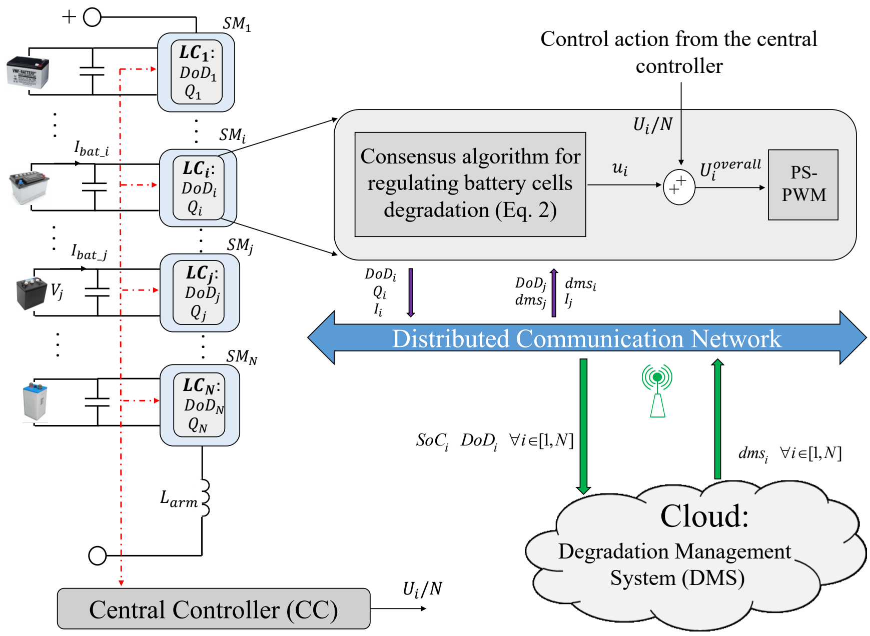


Fig. 3: Implementation of the proposed distributed control scheme for controlling the degradation of battery cells.

at discharge cycle k. Then, at the next cycle $k+1$, the capacity evolves as:

$$Q_i(k+1) = \eta_i(DoD_i(k)) \cdot Q_i(k), \tag{1}$$

where $\eta_i(DoD_i(k))$ is the Coulombic efficiency of the battery cell. This model is thus fully defined by having η_i as a function of $DoD_i(k)$. One usually will have a table for the values of η_i for different $DoD_i(k)$, and the remaining values (those in between) can be found by interpolation. It must be pointed out that these Coulombic efficiencies can be calculated using data provided by the manufacturer that characterises the battery lifespan. Thus, once the cycle is identified, the model characterises cycle k in terms of its $DoD_i(k)$. Then the Coulombic efficiency is found, and finally the capacity for time $k+1$, $Q_i(k+1)$ is obtained.

Note that the simplification of this model is that it is assumed that η_i depends only on $DoD_i(k)$, whereas in [7] it depends both on $DoD_i(k)$ and the *SoC* swing (which is the net difference between the highest and the lowest *SoC* value within a cycle), and in other works [8] it is also affected by other battery parameters such as SR, temperature, and cycles. These effects will be considered in future publications.

Proposed distributed control scheme for controlling battery cells degradation

The proposed control scheme is based on the consensus theory and looks to indirectly regulate battery cell degradation by managing the battery cell discharge policy. Indeed, as is shown in (1), the degradation in the ith battery cell is a function of the *DoD* that undergoes during a given operational cycle. Also, a battery cell with an operating policy that drives it to high *DoDs* will degrade faster than the same battery being managed with an operational approach with lower *DoDs*: This situation motivates the proposed control scheme for battery cell degradation. For instance, let us consider that both the ith and jth battery cells illustrated in Fig. 3 have the same characteristics, but due to their different usage profiles before being recycled to be part of the AC battery, their current capacities are: $Q_i(k) < Q_j(k)$. In this case, for regulating their degradation levels, it is preferable that both battery cells follow the criterion: $DoD_i(k) < DoD_j(k)$ while the AC battery is operating. By doing that, and according to (1), while the AC battery is being used, internally, the jth battery cell is being more degraded than the battery cell ith. To achieve this, the consensus algorithm (2) is proposed. To implement (2), the cyber graph illustrated in Fig. 2 is modelled as an undirected graph $\mathbb{G} = (\mathfrak{N}, \xi, A)$ among the local controllers (*LCs*) $\mathfrak{N} = \{1, ..., N\}$, where ξ is the set of communication links and A is a non-negative $N \times N$ weighted adjacency matrix. The elements of A are $h_{ij} = h_{ji} \geq 0$, with $h_{ij} \geq 0$ if and only if $\{i, j\} \in \xi$ [14]. In this context, the consensus can be reached via a feedback loop by applying the protocol u_i given by (2). This control is distributed because it only depends on the immediate neighbours $j \in \mathfrak{N}(i)$ of node i in the graph topology. Finally, it must be pointed out that the proposed control scheme needs to know the current degradation level of battery cells. For the simulation work presented here, these values are assumed as known. For real applications, this information can be obtained from experimental tests applied to the battery cells before their integration into the AC battery (such as capacity tests and electrochemical impedance spectroscopy [15]).

Note that algorithm (2) regulates the *DoD* of battery cells by manipulating their output currents I_{bat} (see Fig. 3). The term g_i holds the dynamic response of the controller, h_{ij} are the elements of the adjacency matrix A, and the terms dms_i and dms_j are generated by the degradation management system (DMS) to set the usage policies on battery cells (according to some criteria). As was discussed earlier in this paper, the development of the DMP is not addressed here; it is ongoing research and will be published further. However, simulation work discusses and validates some case studies for these terms in the following section.

$$u_i = -\frac{1}{g_i} \sum_{j \in \mathfrak{N}(i)} h_{ij} \cdot \left(\frac{I_{bat\_i}}{dms_i} - \frac{I_{bat\_j}}{dms_j} \right) \tag{2}$$

It must be highlighted that the overall control action $U_i^{overall}$ for the ith *SM*, sent to the modulation stage, comprises two parts, as shown in Fig. 3: U_i is produced by a central controller for regulating active and reactive powers of the proposed AC battery, and u_i is given by the proposed consensus-based distributed scheme (see Fig. 3) for the regulation of battery cells degradation. In this case, u_i is generated by (2), whereas U_i is generated by the central controller reported in [16].

Finally, as seen in Fig. 3, the implementation of the proposed distributed control for regulating the degradation of batteries cells requires that each *LC* compute the following variables (in each battery cell cycle): (i) cycle length calculation, (ii) *DoD* in the identified cycle and (iii) battery cell current. Once this information is calculated (considering the cycle k), the degraded capacity of the ith battery cell, after that cycle, i.e., in the cycle $k+1$, is given by (1).

Simulation Work: Proposal Validation

In this section, the performance of the proposed distributed control scheme for controlling the degradation level of battery cells inside the AC battery is validated via simulation work. To this end, the M2C-based AC battery shown in Fig. 1 is simulated using PLECS software with the parameters listed in Table I. Note in this table that the coulombic efficiencies were arbitrarily selected (following real patterns for these efficiencies [7, 13]) to validate the methodology proposed in this paper and achieve a fast degradation ratio (allowing a sensible simulation time). On the other hand, the central controller (see Fig. 1), in charge of active and reactive power regulation, is implemented in the $\Sigma\Delta\alpha\beta$ reference frame (see [16]), and the battery cells degradation is achieved through the distributed control scheme (2), which implements the discharging policy given by the DMS (dms_i and dms_j in (2)). This section demonstrates that the proposed distributed control scheme illustrated in Figs. 1-3 can control the degradation level of the battery cells that composes the AC battery. In particular, it is shown that the proposed approach can extend the lifespan of the AC battery (and battery cells that compose the AC battery) by properly setting the control actions generated by the DMS (*dms* signals in (2)). For now, these control actions are chosen empirically for two case studies. Both case studies consider that the AC battery is connected to an AC grid, operating with the discharging and charging profile illustrated in Fig. 4. As observed, the AC battery is being discharged in each cycle by power steps of 18kW. Then, it is charged with a power step of the same magnitude (18kW). It must be highlighted that this pattern, along with the small capacities for the battery cells (see Table II and Table III), were selected only for validation purposes as it allows a sensible number of cycles and in an achievable simulation time. Finally, note that the pattern displayed in Fig. 4 is repeated until one or more battery cells reach their usable life. The characteristics of the case studies considered in this paper and the simulation results are presented as follows.

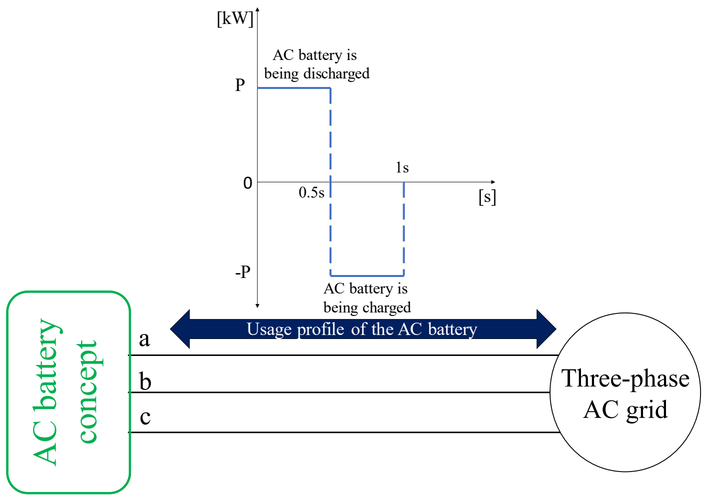


Fig. 4: Main characteristics of the discharging/charging cycle used for operating the AC battery.

Table I: AC battery parameters.

Parameter	Value
Arm inductance (L_{arm})	5mH
SM capacitance (C_{SM})	6mF
No. *SM* per arm (N)	3
Switching frequency (PS-PWM)	8kHz
Active Power reference (P)	18kW
Reactive Power reference (Q)	0Var
Consensus gain (k_i)	1
Coulombic efficiencies as a function of the *DoD* [$\eta(DoD)$] (considered in this work)	$\eta(0.45) = 99\%$ $\eta(0.65) = 98\%$ $\eta(0.85) = 97\%$
Battery cells voltage (V_{bat})	260V

Table II: Parameter of battery cells considered in the case study 1. (Only battery cells related to the upper arm of the phase "a" in the M2C are studied)

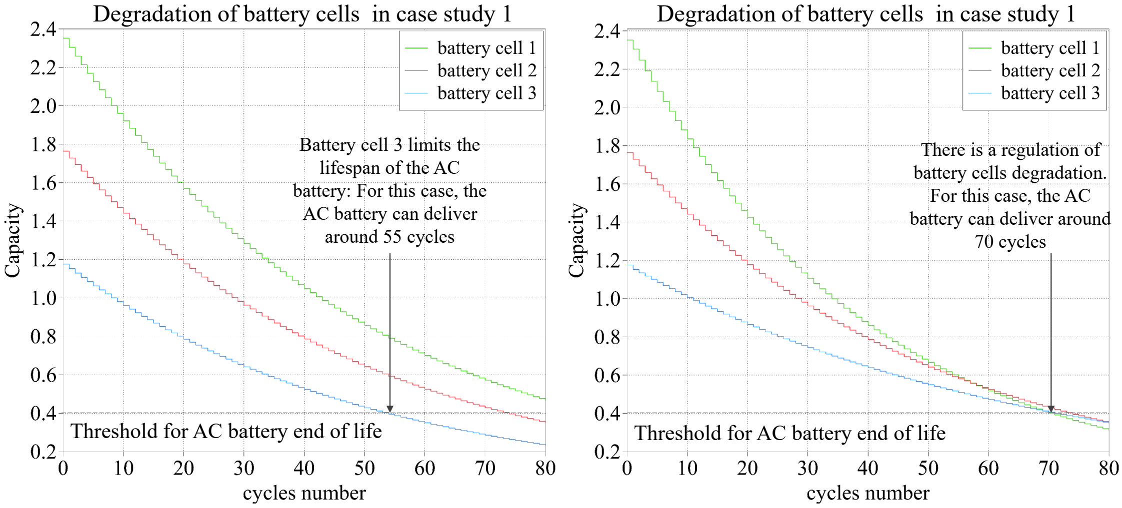
	Nominal Capacity Q_n [As]	Current Capacity	Control actions for the DMS considered in this scenario
Battery cell 1	3	$0.8Q_n$	$dms_1 = 0.8$
Battery cell 2	3	$0.6Q_n$	$dms_2 = 0.6$
Battery cell 3	3	$0.4Q_n$	$dms_3 = 0.4$

Scenario 1

First, for the sake of clarity, the degradation of battery cells associated with the upper arm of phase "a" in the M2C is considered. In this case, it is assumed that all the battery cells composing that arm have the same characteristics (same manufacturer, nominal capacity and nominal voltage). However, due to their use in electromobility applications, their current condition in terms of current capacity (degradation level) is different, as shown in Table II. As seen, battery cell 1 is the less degraded battery, while battery cell 3 is the most degraded one. In this condition, to achieve regulation of those battery cells in terms of their degradation level, the proposed control scheme displayed from Fig. 1 to Fig. 3 and given by (2) is run considering that the control actions generated by the DMS (dms_1, dms_2 and dms_3 in Table II) are set by reason of their current capacities (see Table II). By doing this, battery cell 1 will be operated with a more aggressive policy, in terms of *DoD*, than battery cell 3, while the AC battery is operating. This will equalise the degradation level of these battery cells during the AC battery operation.

Fig. 5(a) shows the evolution of capacities, calculated as (1), for the three battery cells considered in this case study, when the proposed control scheme is not enabled. As seen, for the parameters considered in this test and the discharging/charging profile shown in Fig. 4, it is found that the AC battery can operate until around 55 cycles. After that, the AC battery cannot continue working as battery cell 3 has reached its end of life, limiting the operation of the entire AC battery. In contrast, when the AC battery is working with the proposed distributed control scheme for controlling the degradation of battery cells, it can operate for around 70 cycles, as shown in Fig. 5(b). This result demonstrates that the proposed control scheme can effectively extend the lifespan of the whole AC battery by a proper degradation control of the battery cells that compose it. It must be pointed out that this degradation control is achieved by changing the discharging policy of battery cells, as is illustrated in Fig. 6 after 20 seconds. As observed in that figure, before the 20s, the proposal was not working, and all battery cells were operating with the same policy: they are discharged until a *DoD* of 0.68. Then, after the 20s, when the proposed control scheme is activated, their operating policy is changed, and they operate with a policy proportional (in terms of *DoD*) to their degradation level. By doing this, regulation of their degradation level can be achieved, therefore, increasing the lifespan of the proposed AC battery. Finally, it is worth remembering that the

SoC is calculated, as shown in Fig. 8.



(a) Performance of the AC battery without any control for cells degradation

(b) Performance of the AC battery with the proposed control for cells degradation

Fig. 5: Capacity of battery cells in the upper arm of phase "a" during case study 1: (a) the AC battery is operating without the proposal for degradation control of battery cells, (b) the AC battery is operating with the proposal for degradation control of battery cells: By averaging degradations across cells, prolong the lifetime of the AC battery.

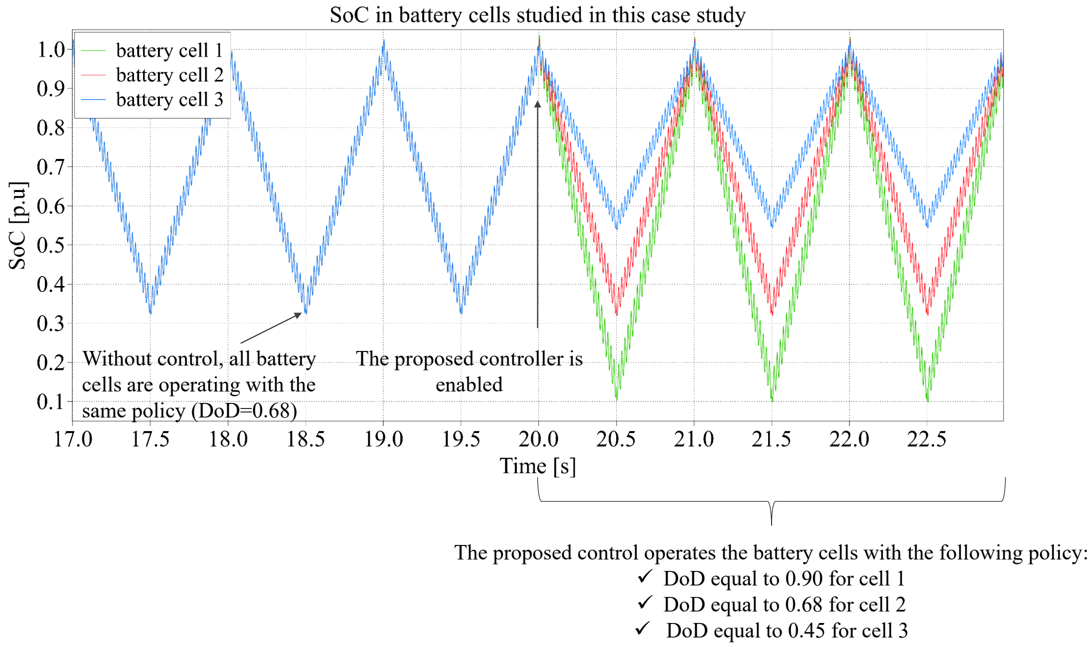


Fig. 6: *SoC* of battery cells in the studied arm during case study 1: before the 20s, the AC battery is operating without the proposal for degradation control of battery cells; after the 20s, the AC battery is running with the proposed control scheme for degradation control of battery cells. (In this figure, six discharging/charging cycles are shown)

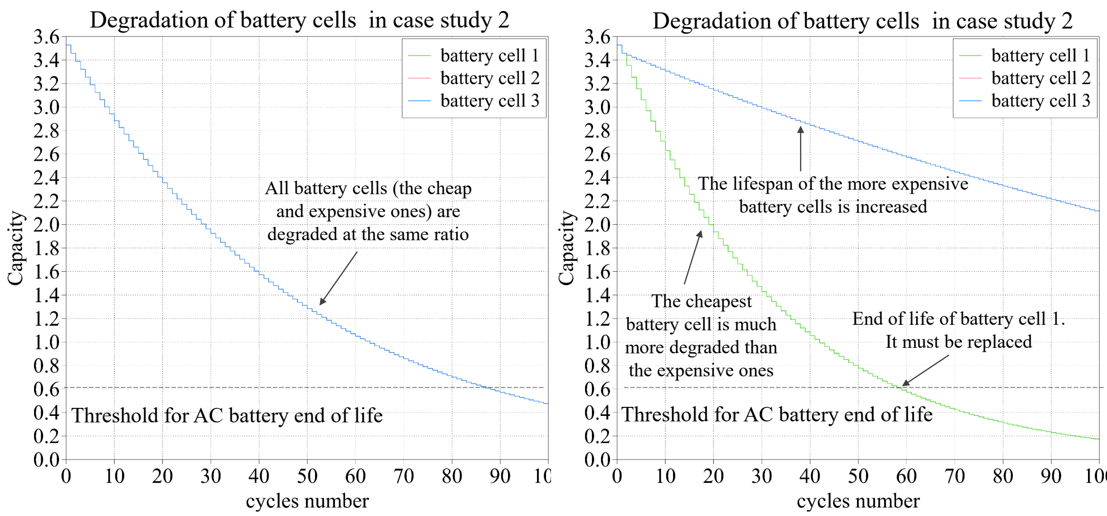
Scenario 2

Similar to case 1, in this case, battery cells related to the upper arm of phase "a" are considered. This case study assumes that battery cells in that arm have the same electrical characteristics but different chemistry. Because of that, battery cell 1 is much cheaper than battery cells 2 and 3. In this condition, the proposed control scheme for degradation purposes could be driven by the DMS considering the

Table III: Parameter of battery cells considered in the case study 2. (Only battery cells related to the upper arm of the phase "a" in the M2C are studied)

	Battery cell cost (a)	Current Capacity	Control actions for the DMS considered in this scenario
Battery cell 1	$0.05a$	$0.6Q_n$	$dms_1 = 20$
Battery cell 2	a	$0.6Q_n$	$dms_2 = 1$
Battery cell 3	a	$0.6Q_n$	$dms_3 = 1$

following control objective: degrade battery cell 1 as much as possible as it is cheaper than others. Thus, the lifespan of battery cells 2 and 3 is prolonged. In this test, the control actions generated by the DMS (dms_1, dms_2 and dms_3) are set for an inverse reason of their costs, as shown in Table III. By doing this, battery cell 1 will be operated with a more aggressive policy, in terms of DoD, than others battery cells. This will prolong the lifespan of battery cells 2 and 3 (the more expensive ones) by highly degrading battery cell 1: This is not an issue in this case, as it is assumed that this battery cell is the cheapest, and there is plenty of availability on the market for buying new ones and replacing it. The results of this test are illustrated in Fig. 7 and Fig. 8. From Fig. 7(a), it is concluded that all the battery cells are degraded in the same ratio without any degradation control, considering this case study's parameters. As was discussed above, from an economic point of view, this situation is not the best because it is preferable to degrade the cheapest battery cell than the expensive ones, to prolong the lifespan of the latter ones. The proposed distributed control scheme achieves this aim, as shown in Fig. 7(b), showing its effectiveness. Additionally, Fig. 8 shows the operating policy used before the activation of the proposal (before 20 seconds) and the operating policy of battery cells when the proposal is working (after 20 seconds). As observed, in this latter situation, battery cell 1 (the cheapest one) has an aggressive discharging policy (DoD close to 0.9), increasing its degradation ratio. Finally, it must be pointed out that, as discussed in [8, 13, 17], managing degradation ratios in a battery system composed of different types of batteries can bring economic benefits, as is the case discussed in this case study. Finally, it is worth remembering that the SoC is calculated, as shown in Fig. 8.



(a) Performance of the AC battery without any control for cells degradation

(b) Performance of the AC battery with the proposed control for cells degradation

Fig. 7: Capacity of battery cells in the upper arm of phase "a" during case study 2: (a) the AC battery is operating without the proposal for degradation control of battery cells, (b) the AC battery is operating with the proposal for degradation control of battery cells.

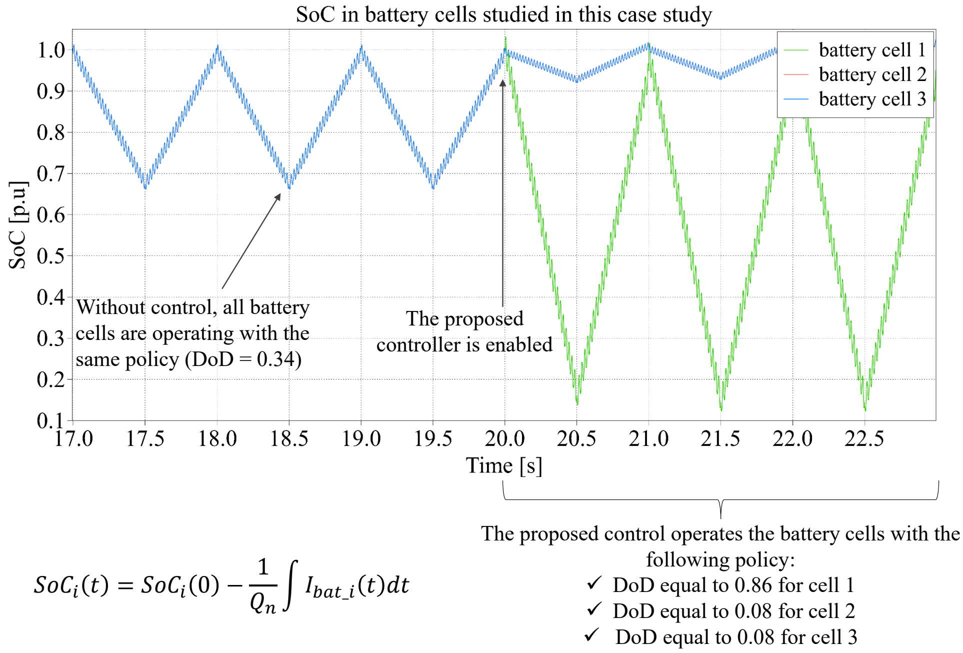


Fig. 8: *SoC* of battery cells in the upper arm of phase “a” during case study 1: before the 20s, the AC battery is operating without the proposal for degradation control of battery cells; after the 20s, the AC battery is running with the proposal for degradation control of battery cells. (In this figure, six discharging/charging cycles are shown)

Conclusions

This paper proposed an AC battery concept based on the M2C that facilitates the use of battery cells (or battery modules composed of one or more battery cells) in second-life applications. The proposed control scheme demonstrated that it can control the degradation level of battery cells that compose the AC battery, bringing economic benefits to the entire AC battery system. Finally, this work demonstrates that the degradation of battery cells can be achieved by the proposed degradation management system (DMS). Note that the case studies and their corresponding parameters were selected to prove the proposed architecture for controlling the degradation of the battery cells (or battery modules composed of one or more battery cells) within the AC battery. Future publications will consider the DMS development and its validation, considering the real operating conditions.

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