# Smart and Hybrid Battery Balancing For Electric Vehicles

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R. de Castro, R.E. Araujo, J.V. Barreras, C. Pinto, "Smart and Hybrid Battery Balancing For Electric Vehicles", 21st IFAC World Congress, 2020, Berlin, Germany.

# Smart and Hybrid Battery Balancing For Electric Vehicles

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**Abstract:** Battery packs of electric vehicles are prone to capacity, thermal, and aging imbalances in their cells, which limit power delivery to the vehicle. Spurred by this issue, we propose a new class of battery balancing systems, called *hybrid battery balancing*, capable of simultaneously equalizing battery capacity and temperature while enabling hybridization with additional storage systems, such as supercapacitors. Our research departs from the current research paradigm, which regards battery equalization and hybridization as two independent functions performed by two separated power converters. In contrast, our concept integrates these two functions into a single system, paving the way for a lower cost of power conversion in hybrid energy storage units. In exchange for reduced hardware costs, this integration of functions poses challenges to the design and control of the hybrid system, such as simultaneously coordinating a large number of power converters, enforcing actuation and safety constraints and making trade-offs between multiple technical and economic objectives. To handle these challenges, we developed constrained and hierarchical optimal control frameworks that rely on convex formulations as a means to obtain computationally efficient control algorithms. Through validation in small scale prototypes, we have demonstrated that this hybrid balancing concept can significantly decrease energy losses and battery stress while increasing a vehicle's range when compared with conventional balancing methods.

*Keywords:* electric vehicles, automotive systems, hybrid energy storage systems, battery balancing, power conversion

## 1. INTRODUCTION

Electrification of the vehicle powertrain is currently envisaged as a key technology in the efforts to make low-carbon transportation a reality. It enables the integration of renewable energies with transportation systems, including road, marine and aerial vehicles, and provides a promising avenue to reduce environmental impact and fuel consumption. As discussed in several technological roadmaps (ERTRAC, 2017; Tsiropoulos et al., 2018) energy storage system represents one of the pivotal areas in electric transportation. However, today's energy storage systems, such as batteries, are still unable to satisfy demanding vehicular requirements, such as higher durability, fast charging capability, reduced volume and mass at a lower cost.

To attenuate these issues, hybrid and modular energy storage systems, composed of heterogeneous units, have been investigated (Chemali et al., 2016). One promising research avenue deals with battery-supercapacitor hybridization. Supercapacitors with high power density and durability are particularly suited to handle rapid power bursts, while battery packs with high energy density can provide average power during vehicle cruising. Numerous works have been exploiting these features to reduce peak-power loads, weight and stress of the battery pack by

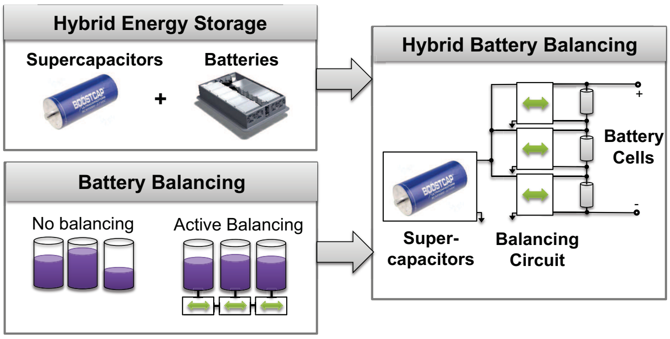
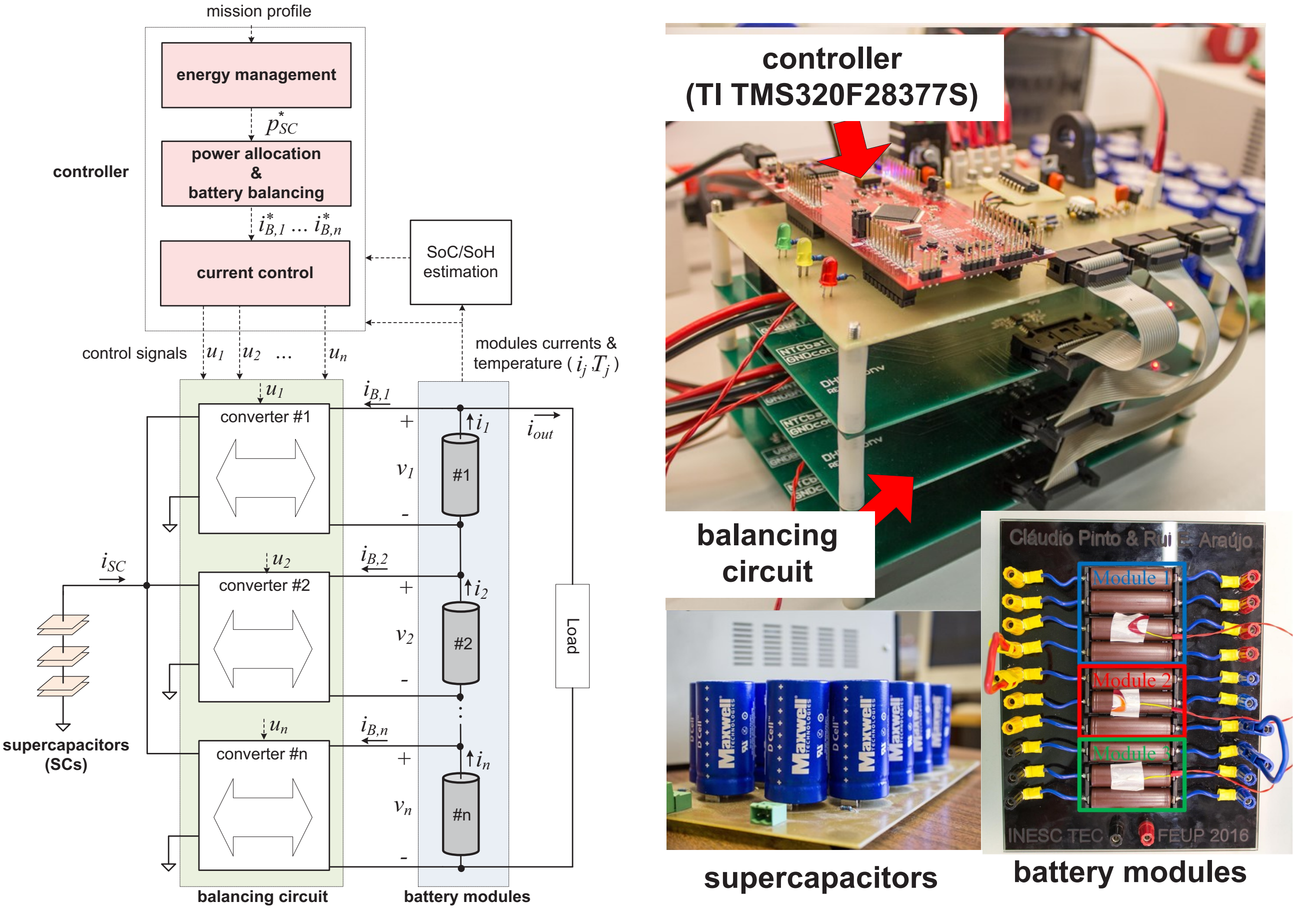


Fig. 1. Concept for hybrid balancing, which combines hybrid energy storage units and battery balancing tasks into one system.



(a)

(b)

Fig. 2. Hybrid balancing system: a) block diagram; b) small-scale experimental setup.

applying optimization-based methods to design, size and control these systems (Araujo et al., 2014; Zhang et al., 2018).

Battery unbalancing is another issue that limits performance of electric vehicles (EVs). Due to high-voltage requirements, batteries packs of EVs contain a large number of cells, inter-connected in series. Because of non-homogeneous characteristics of the cells and non-uniform degradation rates, these large battery packs are prone to cell unbalances on available capacity, available power, and temperature. The battery performance is then limited by the worst cell (or group of cells in parallel) in the string, aka the "weakest link" or the "weakest cell", which constrains acceleration and range of EVs.

Passive balancing systems are nowadays the preferred solution by industry to solve the "weakest cell" problem. Passive systems dissipate energy of cells with higher voltages during charging, enabling cells with lower voltages to be also fully charged at the end of charge. In this way, losses in battery available capacity related to unbalances on initial state-of-charge (SoC) of cells are avoided. This is only a partial solution, since unbalances related to cell-to-cell differences on available capacity, available power, and temperatures will still arise during battery discharge. To mitigate these issues, active balancing has been receiving increased attention in the literature. These approaches use non-dissipative means (e.g. power electronics) to actively transfer energy between cells, ensuring that all cells have a similar SoC and temperature levels at all times (Barreras et al., 2014). As a result, losses in battery available capacity and available power linked to SoC differences are minimized, so vehicle range without derating is extended, and charging times improved (Barreras et al., 2018).

In the literature, the active battery balancing and hybridization (e.g. battery-supercapacitor) has been treated as two independent functions, performed by separate power converters. In contrast, we have been investigating the possibility of integrating these two functions into one system (see Fig. 1). Our concept, called *hybrid balancing system*, exploits the power electronics already embedded in the balancing circuit to simultaneously enable battery equalization and hybridization, avoiding the need to incorporate multiple power converters. This increased level of integration has great potential to reduce hardware costs and raise competitiveness of hybrid energy storage solutions, while posing research challenges for the design, real-time control and implementation of the balancing system. This brief provides a summary of the principle of operation of the *hybrid balancing system* and presents recent results that have been obtained with this innovative concept.

## 2. PRINCIPLE OF OPERATION AND CONTROL METHODS

As depicted in Fig. 2a, the *hybrid balancing system* relies on the integration of power converters with batteries and supercapacitors. The primary side of each converter is connected to an individual battery module—composed of one or more cells—while the secondary side is connected to supercapacitors. This configuration allows the active exchange of energy between different battery modules and supercapacitors. For example, energy from high-capacity modules can be transferred to low-capacity modules as a means to mitigate imbalances in the battery pack. It also enables the transfer of energy to/from the supercapacitors, reducing peak currents and stress in the battery.

Although it provides a flexible mechanism for exchange of energy, the *hybrid balancing system* poses a challenging control problem. This is due to the need to simultaneously control a large number of power converters with several physical and safety constraints and numerous objectives. The overall control goal is usually formulated as a multi-objective optimization problem, aiming to: *i*) minimize energy losses (in the energy storage units and balancing circuit), battery stress and cell-to-cell variations in SoC and temperature, *ii*) while copying with current, voltage and SoC constraints as well as electro-thermal dynamics.

To solve this problem, we have been investigating two types of control architectures. The first is a centralized architecture, where the above-mentioned control problem is solved in a single loop. By exploiting pragmatic simplifications of the batteries' electric and thermal models, convex formulations for the problem can be derived and unique optimal solutions efficiently computed (see de Castro et al. (2019); Pinto et al. (2018) for details). The second approach is based on a hierarchical/multi-loop control architecture (de Castro and Araujo, 2019). The idea is to split the control problem into smaller sub-problems, which, though providing sub-optimal results, are easier to solve. Accordingly, our hierarchical approach is composed of three layers (see Fig. 2a). The first layer focuses on energy management and decides the amount of power aid that the supercapacitors provide to the batteries based on the current driving cycle. The second layer is responsible for battery equalization and for allocating the supercapacitors' power reference (requested by the energy management layer) among the balancing circuit. The third layer tackles the control of the balancing circuit, such as current loops.

Because of its high complexity and computational effort, the single-loop architecture is mainly employed as an off-line tool to generate benchmark results for the *hybrid balancing system*, while the hierarchical architecture is more suitable for the on-line implementation of the controller in embedded systems. An additional benefit of the hierarchical architecture is the high degree of modularity. This feature is particularly attractive because it allows us to re-use state-of-the-art methods to handle some of the control layers. For example, at the energy management layer, numerous optimal (Nguyen et al., 2018), learning-based (Alobeidli and Khadkikar, 2018) and heuristic (Ahmed Ali and Dirk Söffker, 2018) methods–which have been previously proposed to split the power between multiple energy storage units–can be straightforwardly integrated into *hybrid balancing system*. Likewise, practical PID controllers and pulse-width modulators can be deployed in the lower control level (Pinto, 2018).

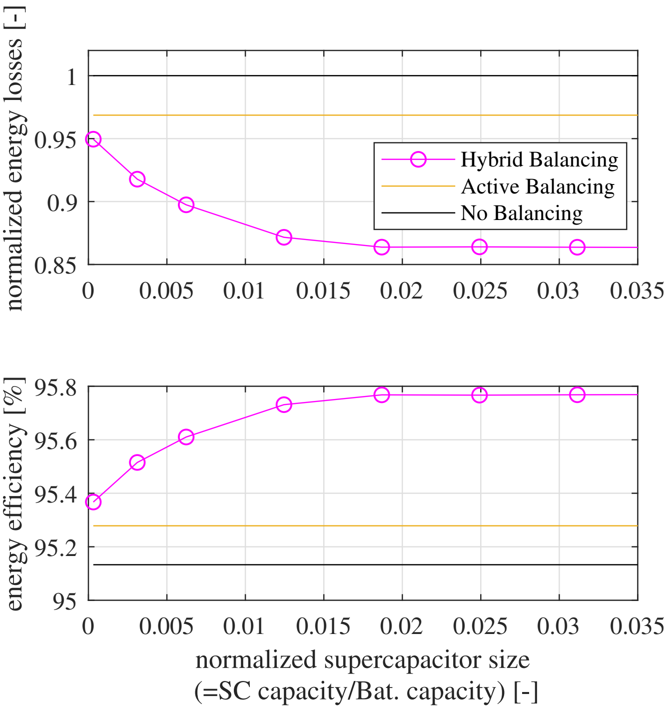
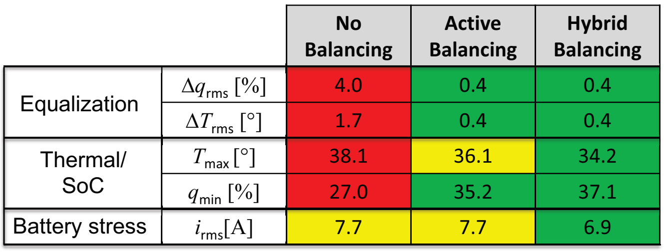


Fig. 3. Energy efficiency and energy losses of hybrid balancing, active balancing and no balancing (note: energy losses are normalized with respect to no balancing configuration).

Table 1. Performance metrics of different battery balancing variants



| | | No Balancing | Active Balancing | Hybrid Balancing |
|---|---|---|---|---|
| Equalization | $\Delta q_{\text{rms}}$ [%] | 4.0 | 0.4 | 0.4 |
| | $\Delta T_{\text{rms}}$ [°] | 1.7 | 0.4 | 0.4 |
| Thermal/ SoC | $T_{\text{max}}$ [°] | 38.1 | 36.1 | 34.2 |
| | $q_{\text{min}}$ [%] | 27.0 | 35.2 | 37.1 |
| Battery stress | $i_{\text{rms}}$[A] | 7.7 | 7.7 | 6.9 |

Note: green, yellow and red color represent very good, average and poor performance, respectively.

## 3. RESULTS AND DISCUSSION

To validate the *hybrid balancing system* a small-scale prototype was built (Fig. 2b). It is composed of 10 battery cells (18650 Li-ion cells) arranged in three series-connected modules: the first module has 4 parallel cells while the last two modules have 3 parallel cells. This arrangement artificially emulates capacity imbalances that might be found at end-of-life battery packs. The secondary energy storage unit is based on supercapacitors (Maxwell BCAP0310 P270 T10), while the balancing circuit was implemented through dual-half bridge power converters. As reference vehicle, we considered a scaled version of the uCar prototype (Araujo et al., 2014) and employed the US06 (repeated 5 times) as reference driving cycle.

Sizing of the supercapacitors is an important design decision that affects performance of the energy storage system. To gain insights into this design issue, Fig. 3 depicts the energy losses of the *hybrid balancing system* for different sizes of the supercapacitors (normalized with respect to battery's capacity). The results reveal that the energy losses decrease as the supercapacitors' size becomes larger, saturating when the supercapacitors reach 2% of the battery capacity. This saturation is due to the increased energy losses in the balancing circuit that occur with larger supercapacitors (which also demand higher currents), canceling the energy efficiency benefits offered by supercapacitors. The results also show that the *hybrid balancing system* is able to decrease the energy losses in 10% and 14% when compared to active balancing and no balancing variants, respectively, contributing to an increase of 0.7% in the overall energy efficiency.

Table 1 compares the performance of the *hybrid balancing* against the active balancing and no balancing variants. This comparison considers the following performance metrics:

- root-mean-square of the cell-to-cell variations in the SoC and temperature ($\Delta q_{rms}, \Delta T_{rms}$)
- maximum temperature and minimum SoC at the end of the driving cycle ($T_{max}, q_{min}$)
- battery stress, measured in terms of root-mean-square ($i_{rms}$)

Inspecting the results, one can find that both hybrid balancing and active balancing provide similar equalization performance, reducing in up to 10x the cell-cell SoC variations when compared to the no balancing variant. Because of this good equalization performance, the final SoC reached by the active and hybrid variants increases 8% and 10%, respectively, attenuating the weakest-cell problem, and allowing the EV to drive longer journey per charge. Moreover, the *hybrid balancing system* also decreases the maximum temperature in the battery cells from 2°C to 4°C and the battery current stress in 10%. These features are particularly relevant, not only to improve energy efficiency, but also to reduce degradation and thermal load of the battery back, enabling longer battery lifetime and reducing cooling needs.

## 4. OUTLOOK

The reduction of battery degradation offered by *hybrid balancing system* might be particularly attractive to second-life applications. Despite their inability to comply with strict automotive requirements, end-of-life batteries of EVs might still retain enough capacity and performance to fulfill the needs of less demanding applications, such as grid support. Our future research will investigate how the reduced battery degradation obtained with the *hybrid balancing system* during the batteries' first life (inside the vehicle) can raise their economic value for second-life applications.

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