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# Active model-based balancing strategy for self-reconfigurable batteries

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## HIGHLIGHTS

- Cell balancing in a self-reconfigurable battery is formulated as network optimization.
- Investigation of the dynamic programming techniques to solve the optimization problem.
- Battery simulations are performed based on battery model by different input parameters.
- The performance of the proposed balancing strategy is proofed.

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## ABSTRACT

This paper describes a novel balancing strategy for self-reconfigurable batteries where the discharge and charge rates of each cell can be controlled. While much effort has been focused on improving the hardware architecture of self-reconfigurable batteries, energy equalization algorithms have not been systematically optimized in terms of maximizing the efficiency of the balancing system. Our approach includes aspects of such optimization theory. We develop a balancing strategy for optimal control of the discharge rate of battery cells. We first formulate the cell balancing as a nonlinear optimal control problem, which is modeled afterward as a network program. Using dynamic programming techniques and MATLAB's vectorization feature, we solve the optimal control problem by generating the optimal battery operation policy for a given drive cycle. The simulation results show that the proposed strategy efficiently balances the cells over the life of the battery, an obvious advantage that is absent in the other conventional approaches. Our algorithm is shown to be robust when tested against different influencing parameters varying over wide spectrum on different drive cycles. Furthermore, due to the little computation time and the proved low sensitivity to the inaccurate power predictions, our strategy can be integrated in a real-time system.



## 1. Introduction

Nowadays, Battery Electrical Vehicles (BEVs) are widely accepted as a very promising alternative to the conventional fossil fuel based vehicles. The main power sources of these vehicles are battery systems having a large number of serial and/or parallel connected cells. In those batteries, Lithium-ion technology is widely applied due to its low self-discharge rate and high energy density. Unfortunately, neither an ideal manufacturing process is present nor exact cell classification (in terms of capacity selection) is possible. Hence, the cells in the same battery stack show different electrical characteristics such as impedance and aging behavior. The cell capacity variance becomes more and more significant over lifetime due to internal factors (such as capacity degradation, impedance increase) and external factors (such as operation conditions and temperature). This cell imbalance results in two major problems: first of all, it reduces the effective discharge time. In fact, the battery management system (BMS) cuts off the whole battery once the first cell reaches the minimal voltage limitation even though other cells are still usable. Thus, a portion of energy remains unusable in the battery pack. It is called residual energy $E_{res}$. Moreover, due to the voltage difference of the cells that are connected in series, the weaker cells may become under- or

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overcharged. Both scenarios can lead to failure of the battery and/or reduce the battery life time.

To address this issue, cell balancing circuits are used. In the literature, a number of different topologies have been proposed. These can be classified into two major categories: active balancing and passive balancing ([1,2], and [3]). The passive balancing dissipates the excess energy through shunt resistors in the form of heat. Active balancing transfers the electrical charge from the cell with higher energy content to the cell with lower energy content. A review of the literature shows that a lot of research has been carried out in the field of active balancing. Different topologies are reported depending on which energy storage component, capacitors or inductive elements, are used [4]. Switched capacitor based topologies are widely discussed due to their simple control and robustness ([5,6], and [7]).

In those topologies, all battery cells are permanently connected to the load. So, in case of failure of a single cell the whole cell string will fail. Furthermore, due to the limited balancing current, if the cell capacity deviation is major, the balancing time becomes too long to avoid capacity reduction of the battery system. Therefore, the conventional active balancing topologies cannot widen the available capacity range in case of high imbalanced or damaged cells.

To overcome this limitation, self-reconfigurable batteries could be an effective solution. Two main architectures can be configured. Guertlschmid et al. presented in Ref. [8] a topology that deploys a power converter (DC/DC) for each battery cell. The cells are connected in series while the power converters are connected in parallel to each cell. Through the DC/DC converters, it is possible to control the discharge or charge rate of each cell independently. The structure of the battery system is shown in Fig. 1a). In order to achieve efficient and feasible management of the high voltage battery, the authors proposed a control strategy involves the calculation of the equalization current which is proportional to the cell capacity.

An alternative concept is presented in Refs. [9] and [10] and shown in Fig. 1b); the cell and the DC/DC converter built a power unit. While the battery cells are decoupled, the power units are serially connected. To control the discharge and charge rates of each cell, two control loops with different multipliers were introduced. The target is a rapid cell balancing which unfortunately provokes unnecessary heat and more energy loss. In addition, if one cell is damaged, the whole string is defective. Another widely discussed self-reconfigurable topology consists of serially connected single cell units, where each single unit has a battery cell with two associated switches to connect or bypass it [11], as shown Fig. 1c).

This paper does not focus on the hardware topologies; rather it presents an active, model-based balancing strategy for self-reconfigurable batteries according to the topologies presented in Fig. 1. Similar strategies have been reported in the literature. In Ref. [12] several rule-based control algorithms have been proposed. The simplest used technique is to disconnect the empty or damaged cells. This strategy is limited due to the minimum system voltage limit. To address this limitation, another control strategy is presented in Ref. [12]. The battery cells are classified based of their state of charge (SoC) and the one with least charge (which is not necessarily empty or damaged) will be disconnected. Maneti et al. improved this approach by introducing an analytical estimation of the suitable time interval to decide which cell should be deactivated [13]. A main disadvantage of this method is that the number of bypassed cells is predetermined regardless of the capacity variance of the battery or driver's power demands, although the power peaks have an important impact on the performance of the balancing strategy.

Our work is motivated by the fact that enhanced battery energy efficiency does not only originate from hardware topologies but also from the intelligent operation strategy. Note that the energy efficiency is the amount of useful energy extracted from the system divided by the total input energy.

In this work the cell balancing is formulated as an optimal control problem. This optimization problem is solved through network modeling. Furthermore, the proposed algorithm incorporates knowledge about vehicle power demand in order to achieve global optimal energy equalization in the battery. More specifically, the optimization outcome is an efficient battery management policy perfectly adapted to the entire drive cycle. The designed strategy is applicable in real-time application due to the little computation time and high robustness.

The paper is structured as followed. Section 2 addresses the problem formulation. In Section 3 the network modeling and the operation principle of the proposed system are analyzed. Simulation results and discussion are presented in section 4. Finally, a conclusion is drawn in section 5.

## 2. Optimal control approach for cell balancing

As reported in the previous section, the architecture of self-reconfigurable batteries is well known. In this work, the idea is to use it along with an energy balancing algorithm based on optimization of the discharge/charge rate of each battery cell. In our approach, we presume that the battery will be discharged with a standard drive cycle. Our objective is to achieve an optimal cell

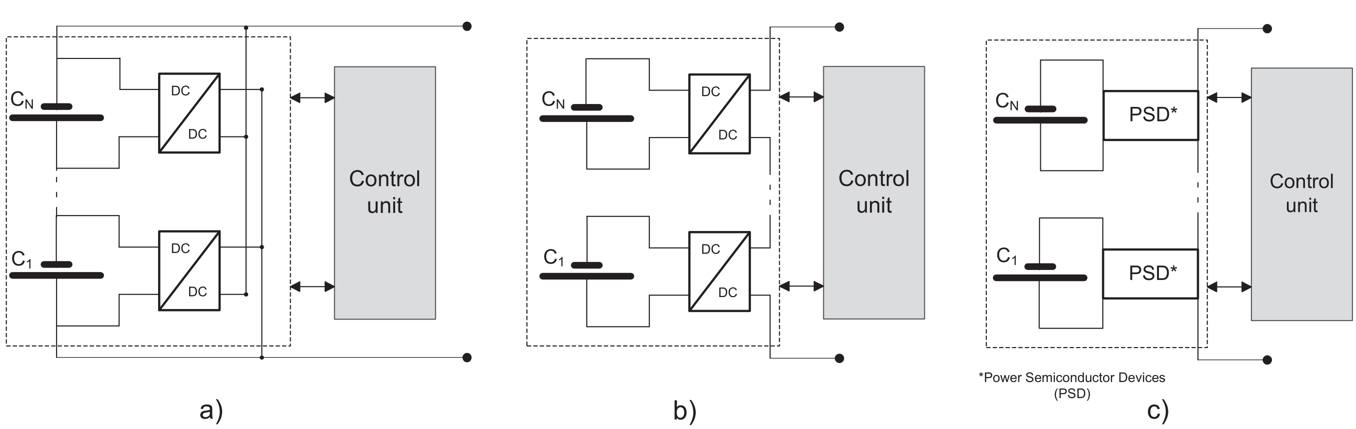


**Fig. 1.** Simplified diagram of the different self-reconfigurable battery topologies: a) DC/DC connected in parallel to each cell. b) Serially connected 'Cell-DC/DC' unit. c) Serially connected 'Cell-PSD' unit.