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Design of novel charge balancing networks in battery packs

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HIGHLIGHTS

- We consider the performance of charge balancing systems for multi-cell battery packs.
- The performance is measured by the voltage equalization rate and the steady-state cell unbalance.
- The performance depends on the topology of the cell-to-cell connections.
- The performance can be correlated with graph theoretic properties of the underlying network.

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ABSTRACT

In a modern battery pack, the charge in the individual cells can diverge in time, leading to decreased capacity and reduced operating life of the pack. Charge balancing systems can be introduced to equalize the state of charge across the multiple cells, therefore increasing the performance of the battery pack. This work considers the dynamic performance of charge balancing systems, and through simulation explores how their ability to equalize the state of charge depends on the design of the underlying charge balancing network. The performance of the charge balancing system is described in terms of the rate at which the individual cells converge and the maximum cell voltage deviation in the pack. Specifically the performance of the charge balancing system is shown to correlate with graph theoretic properties of the underlying charge balancing network, including the diameter and spectral gap. Several different underlying charge balancing networks are considered, applied to an 8-cell pack, with two parallel strings of four cells in series.

1. Introduction

Modern battery packs are composed of multiple cells, combined to achieve required voltage and current levels. Four main networks can be identified that allow for individual cells to interact with one another; the power network, the communication network, the balancing network, and the safety network. The power network transfers energy from the individual cells in the pack, through the pack terminals, and into an attached load. The communication network transfers information about each of the cells throughout the pack, and often to a pack manager and a user information console. The balancing network transfers charge throughout the pack to maintain a balanced state-of-charge among the individual cells (or a balanced state-of-energy). Finally, the safety network carries pack reconfiguration information throughout the pack, allowing for the restructuring of the pack when a fault condition is detected. Clearly, each of these networks requires specific hardware to accomplish its task, however varying degrees of functionality compete with complexity and cost in the construction of a real pack. Thus every pack trades off the functionality of each topology with its cost. The purpose of this paper is to provide a framework for the understanding and design of cell balancing networks, and how their topology influences the ability of the pack to achieve a balanced state.

Ideally each individual cell in a battery pack has identical characteristics, so that they all react identically to various stimuli. However, in practice the individual cell characteristic parameters vary from cell to cell due to, for example, manufacturing differences,

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environmental conditions such as localized temperature in the pack, or an evolving damage state of the cell. Some cells will have increased self-discharge rates. Some will have higher voltages due to their temperature. Some will have higher internal resistances causing voltage variation and heating. In nearly every battery pack, individual cell characteristics will diverge from those of the other cells in their pack. Historically, with lead and nickel based chemistries, the cells could be brought into balance by overcharging the full cells while the continuing to charge cells that had yet to reach their charge capacity. Major damage in the full cells was avoided by reducing the overall pack current as the pack voltage reached some predetermined level. Unfortunately, the modern lithium based chemistries do not allow overcharging of individual cells without significantly shortening their useful life. Thus, some form of cell balancing is usually required for lithium based chemistries [1–5].

To overcome this scenario, a charge balancing system can be introduced, whereby charge is shuttled from one cell to another to balance the state of charge across the pack [6–8]. Balancing in the charging cycle is often accomplished by using bypasses. When a cell is approaching a full state, a current bypass is often turned on to reduce the current flowing to the cell. The diverted current is usually passed through a resistor where the energy is converted to heat. Thus, this method can result in significant energy inefficiency and is only active during the charging sequence.

Another approach to balancing is the use of a flying capacitor [9]. This capacitor requires switches to connect its terminals to the terminals of every cell in the pack. The capacitor can then take charge from high voltage cells, and transfer it into low voltage cells. A problem with this approach is the serious decrease in pack reliability due to the possible failure of the large number of switches. Another problem is the heating of the switches when they close due to large voltage mismatches and thus high currents. Yet another problem is that only one charge transfer can occur at a time if only one flying-capacitor is used. These concerns also apply to strings of parallel flying-capacitors, as well as DC–DC converter structures using many parallel inductors.

The third main approach to balancing is the use of transformers. Some multi-transformer based balancers will take energy from individual cells, and then place it back into the entire pack where it is distributed among all the cells. Another approach is to use a two-terminal transformer to take charge from an individual cell, and to place it into another individual cell [6–8]. This approach has the benefit of having all the cells electrically isolated from all the others, as the energy is transferred through magnetic fields in the transformer cores. Another benefit is that all of the transformers can be engaged simultaneously. However, the charge balancing system is limited by the number of connections between cells. For a pack with N total cells, the number of connections required to connect each cell to every other cell is $N(N-1)/2$, which can become unacceptably large as the total number of cells increases. Thus, a smaller number of connections is used, and the topology of that balancing network greatly influences the ability of the charge balancing system to maintain an equal state of charge across the pack.

The pack can be represented by a graph, where the nodes of the graph represent the individual cells and the connections between the cells are the edges of the graph. For a battery pack with a charge balancing system two natural graphs can be identified—the first corresponds to the delivery of power by the battery pack and the second represents the charge balancing system itself. The power topology describes the series and parallel combinations that form the battery pack and is typically determined by the load requirements, while the balancing topology is a design variable. It is assumed that each cell will contain some type of control knowledge, and that it can transfer charge to other cells through bidirectional links. Here undirected graphs are used, although directed graphs could be applied if the balancers can only transfer charge in one direction. Finally, the controller design is local in nature, so that the interaction between cells depends only on the charge in the connected cells, and is not specified by a global observer.

This work explores the dynamics of the overall battery pack/charge balancing systems and specifically the influence of the balancing topology design on the overall performance of the charge balancing system. The appropriate model for the battery pack, including the power topology and the individual cell models, is given in Section 2, together with the charge transfer model. In Section 3 appropriate measures of the balancing performance are defined and significant graph characteristics are identified. These ideas are explored in Section 4, as applied an 8-cell pack, with two parallel strings of four cells in series. Finally, concluding remarks are given in Section 5.

2. Model

2.1. Battery pack

Here we consider an $S \times P$ network for the power delivery in the pack, with S cells in series, composing a single strand, and then P strands connected in parallel. The pack illustrated in Fig. 1a would therefore be a 5×4 power network, or a $5S4P$ network using common notation. The total current and voltage through the pack is given by I_ℓ and V_ℓ respectively, while individual cells are indexed as jk, with $j = 1,\ldots,S$ and $k = 1,\ldots,P$. The quantity I_{jk} represents the current through an individual cell and V_{jk} measures the voltage across the corresponding cell. In terms of the individual cells, the pack current and voltage can be determined as

$$V_\ell = V_k, \quad V_k = \sum_{j=1}^{S} V_{jk}, \tag{1a}$$

$$I_\ell = \sum_{k=1}^{P} I_k, \quad I_{jk} = I_k. \tag{1b}$$

Physically the current through the kth parallel strand is I_k while V_k is the voltage across this strand of cells. This pack is then subjected to an appropriate load characterized as either *i*) current controlled ($I_\ell = \text{constant}$), *ii*) voltage controlled ($V_\ell = \text{constant}$), or *iii*) resistive ($V_\ell = R_\ell I_\ell$).

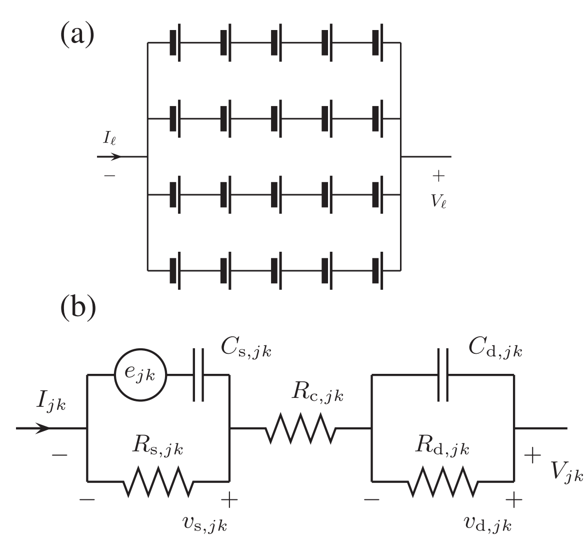

Fig. 1. Battery model; (a) pack power topology, (b) individual cell.