Modular battery charge equalization circuit based on state of charge for electric vehicle application

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Abstract. Electric Vehicle (EV)/ Hybrid Electric Vehicle (HEV) enabled by high-efficiency electric motor and controller, provide the means for a clean, efficient and environmental friendly transportation system. Portable rechargeable batteries are the essential basic component in EVs. In EV/HEV system a large number of cells should be connected in series to supply enough energy, while the voltage balancing problem between cells leads to poor performance. This paper attempts modular battery charge equalization based on state of charge (SOC) under MATLAB Simulink environment.

Keywords: Electric Vehicle/ Hybrid Electric Vehicle (EV/HEV), State of Charge (SOC), Battery Management System (BMS).

1. Introduction
Advanced vehicle technologies alternative to the conventional IC engine vehicles are referred to as alternative vehicles. Electric vehicle (EV), hybrid electric vehicle (HEV), plug-in hybrid vehicle (PHEV) and fuel cell electric vehicle (FCEV) are the examples of alternative vehicles. The main characteristic of EVs/HEVs is that the electrical energy would be efficiently utilized to power electric motors for propulsion. The battery is a fundamental component of electric vehicles, which represent a step forward towards sustainable mobility [1]. Rechargeable batteries such as Lithium ion batteries are widely used in automobile industry because of its high energy density, high power density, long cycling life etc.,

The battery management system (BMS) is a critical component of electric and hybrid electric vehicles [2]. The nominal voltage of a lead-acid cell is 2V whereas lithium-ion cell is about 3.65 V and it varies based on cell type. Applications, such as telecommunication systems, uninterruptible power supplies (UPSs), and off-grid solar energy systems require voltages ranging from 12 V nominal to 300 V or more with dozens of stacked cell in series-parallel modules. Electric Vehicle applications often use 300 V-400 V strings. The energy storage device in an EV, consist of number of cells connected in series string to deliver required voltage. The characteristics of individual battery cells could be different in a long string, due to natural dispersion during manufacturing, chemical degradation and ambient temperature variation during charging and discharging [3-4]. As a result, the battery voltages through the entire string are not uniform during the charging and discharging cycle.
The state of charge (SOC) represents the present capacity of the battery. If the SOCs of stacked batteries are different, it lead to overcharge or over discharge condition which in turn reduce the capacity of the cell and pack. Sophisticated battery users are aware that SOC balance is necessary, particularly for lithium-ion types.

Lithium-ion batteries pose a significant safety risk if over-charged. If the voltage across a single cell becomes higher than 4.3 V, a flammable metallic lithium is formed. If the cell voltage is less than 2.5 V, metallic copper as well as a short circuit is formed, leads to heating and even a catastrophic failure. In both charge and discharge modes, a certain magnitude of current creates unequal voltage drop across cells if their electrochemical properties are not completely matched, and this is very likely to happen in the real world. Therefore, it is absolutely necessary to employ a cell equalizer, which is far more feasible than developing manufacturing technology, in order to eliminate the cell unbalancing.

Cells with higher capacities reach full capacity before the others, and cells with smaller capacities tend to discharge quickly as shown in figure 1. Cell unbalance problem tends to be worse through continuous charging and discharging cycles.

![Figure 1](image_url)

In this paper, two balancing methods, using an external charger and switched capacitor are analyzed based on the simulation works by considering the SOC of the modular batteries in MATLAB Simulink environment. Section II describes the typical battery balancing method and switched capacitor (SC) method, section III presents the necessity of SOC based balancing method, section IV deals with the simulation works and results of two balancing methods by considering two cases of SOC and cell voltage and section V gives the conclusion.

2. Battery Balancing Method

The available energy stored in a battery cell is $E_{\text{val}} = qV$, which states that both charge and voltage need to be balanced in a series string to maximize the output of a pack. The simplest strategy adopted for charging a series connected string of cells is to monitor the cell voltages and discontinue charging when one of the cells (strongest cell) reaches the voltage limit for individual cells [5]. Extended charging is another option where charging is continued even after the strongest cell has reached its capacity to bring the weaker cells up to capacity as shown in figure 2. Cell balancing circuit consisting of three cells B1, B2 and B3 connected in series along with S1-S10 switches. The first task is to read the battery voltages. This is done by switches S1, S2 and S3. There is a dedicated path to each battery with the switches so as to route the charging current to the identified weakest battery.

The simplest protection during discharge of a pack is to shut down when the first cell (weakest cell) reaches the minimum voltage limit. But this method of charging or discharging prevents the effective utilization of battery pack as a whole. Therefore various balancing methods are adopted in considerations of energy consumption and transformation. They can be divided into dissipative balancing circuits and non-dissipative balancing circuits. Dissipative balancing circuits violate the future trend of energy-saving, although it is practical with simple topologic and convenient control strategy.
One of the non-dissipative methods is switched capacitor method [6-8]. The basic SC equalization circuit is shown in figure 3. There are two sets of switches. Set one (S1, S3 and S5) connects the switched capacitors to all of the positive battery terminals, while set two (S2, S4 and S6) connects the switched capacitors to all of the negative battery terminals.

The two sets are switched alternately. The switched capacitor voltages do not change much, but are switched at a high enough frequency to move charge between adjacent batteries. The direction of current flow will depend on the relative voltages of the adjacent batteries and may vary throughout the pack.

3. SOC based charge equalization and its necessity.
SOC is the amount of capacity that remains after discharge from a top-of-charge condition. If the string is treated as a two terminal device while being charged and discharged, the individual cells will have different states of charge [9]. Because of this different SOC some cells will be chronically overcharged, undercharged or over-discharged. Over many cycles, this tends toward capacity decrease for the cell and the pack. If this unbalance remains in the pack, several cells are underutilized, causing the reduced cycle life for the entire battery pack. Therefore, keeping the SOCs of the cells at a uniform level thereby voltages is critical for enhancing the battery life.

4. Simulation Results
In this paper, balancing circuit using an external charger and switched capacitor methods are simulated using MATLAB Simulink environment. Lithium-ion battery parameters used for simulation are listed as shown in table 1.
Table 1. Lithium-ion battery parameters

| Parameters                        | Values |
|-----------------------------------|--------|
| Nominal Voltage (V)               | 11     |
| Rated Capacity (Ah)               | 42     |
| Initial SOC (%)                   | 100    |
| Maximum Capacity (Ah)             | 44     |
| Fully Charged Voltage (V)         | 12     |
| Nominal Discharge Current (A)     | 3.5    |
| Internal Resistance (ohm)         | 0.002  |

In each circuit two cases are considered. In the first case SOCs of all the cells are equal and 100% but the cell voltages are different. In the second case both SOC and cell voltages are different.

4.1. Case I: Same SOC and Different Voltage

In this case all the batteries have same SOC in both circuits and different voltages. The values are listed in table 2.

Table 2. Condition: Same SOC and Different Voltage

| Battery | SOC  | Initial cell voltage | Final cell voltage in external charger circuit | Final cell voltage in switched capacitor circuit |
|---------|------|-----------------------|-----------------------------------------------|-----------------------------------------------|
| B1      | 100  | 10.8                  | 12.02                                         | 11.89                                         |
| B2      | 100  | 11                    | 12.02                                         | 11.89                                         |
| B2      | 100  | 11.5                  | 12.02                                         | 11.89                                         |

If SOCs are equal, all the cells attain balanced voltage irrespective of its equalization method. But in external charger balancing circuit, there is a possibility of overcharging. In table 2, set condition is same SOC and different cell voltages, and the voltage to be balanced is 12V. But the balanced cell voltage of external charger is 12.02V slightly above the preset value of 12V. This one of the draw backs of external charger method. Figure 4 and figure 5 represent the plot corresponding to the same SOC and different voltage condition.
Figure 4. Case 1: Balanced cell voltages of external charger method

Figure 5. Case 1: Balanced cell voltages of switched capacitor method.

In figure 5 it is clear that all batteries are balanced and closely settled to the set value of 12V without overcharge.

4.2. Case II: Different SOC and Different Voltage

In this case all the batteries have same SOC in both circuits and different voltages. The values are listed in table 3.

| Battery | SOC | Initial cell voltage | Final cell voltage in external charger circuit | Final cell voltage in switched capacitor circuit |
|---------|-----|----------------------|-----------------------------------------------|-----------------------------------------------|
| B1      | 90  | 10.8                 | 12.45                                         | 11.90                                         |
| B2      | 97  | 11                   | 12.01                                         | 11.91                                         |
| B2      | 100 | 11.5                 | 12.02                                         | 11.90                                         |
This case describes the behavior of external circuit and switched capacitor circuit under different SOC. The plots corresponding to that are shown in figure 6 and figure 7. In different SOC condition cell voltage of external charger circuit is not balanced and all are exceed the set value of 12V. Over discharge may also be happened in the similar way during discharging cycle. In SC method all the cell voltages are balanced and within the set limit of 12V.

![Figure 6. Case 2: Cell voltages of external charger method](image)

**Figure 6.** Case 2: Cell voltages of external charger method

![Figure 7. Case 2: Balanced cell voltages of SC method](image)

**Figure 7.** Case 2: Balanced cell voltages of SC method

Thus by using non-dissipative cell balancing method (Active balancing method) like SC method overcharge and over discharge can be eliminated

5. **Conclusion and Future Scope**

An external charger and switched-capacitor equalization methods are analyzed through MATLAB simulation. Plots of the balanced cell voltages are also shown. The primary advantage of an external charger method is its simplicity. The main limitation of this technique is over charge condition, increased number of switches and low efficiency operation. Active method of cell balancing is very essential component in BMS especially in high power applications such as EV/HEV applications [10-11]. The switched capacitor method discussed in this paper requires a long equalization time compared to low efficient external charger method. To solve the deficiency, utilization of a high-performance control strategy is essential. Fuzzy control is beneficial to reduce balancing time, while Proportional Integral (PI) control is an effective method to improve balancing accuracy.
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