Design of a Charge Equalizer Based on Battery Modularization

Hong-Sun Park, Chol-Ho Kim, and Gun-Woo Moon
Division of Electrical Engineering, KAIST
Tel. 042-869-3475 Fax. 042-869-8520
Email: gwmoon@ee.kaist.ac.kr

Abstract − The charge equalizer design for a series connected battery string is very challenging because it needs to satisfy many requirements such as implementation possibility, equalization speed, equalization efficiency, controller complexity, size and cost issues, voltage and current stress, and so on. Numerous algorithms and circuits were developed to meet the above demands and some interesting results have been obtained through them. However, for a large number of cells, for example, eighty or more batteries, the previous approaches might cause problems. Such problems include long equalization time, high controller complexity, bulky size, high implementation cost, and high voltage and current stress. To overcome these circumstances, this paper proposes a charge equalizer design method based on a battery modularization technique. In this method, the number of cells that we consider in an equalizer design procedure can be effectively reduces; thus, designing a charge equalizer becomes much easier. Furthermore, by applying the previously verified charge equalizers to the intramodule and the outer-module, we can obtain easy design of a charge equalizer and good charge balancing performance. Several examples and experimental results are presented to demonstrate the usefulness of the charge equalizer design method.

1. Introduction

Series connected battery strings have been used for many applications, such as electric vehicles, hybrid electric vehicles (HEVs), electric scooters, and uninterruptible power supplies. Of these, an HEV battery is severely exposed to a charge and discharge environment because an HEV can recover energy from the wheels during regenerative braking (an energy source that was wasted in the past) and reuse it to propel the vehicle at low speeds or provide extra power for high acceleration. This repeated charge and discharge phenomenon causes a cell mismatch problem. And when these imbalanced batteries are left in use without any control, such as cell equalization, the energy storage capacity decreases severely [1] and, in the worst case, there may be an explosion or fire [2]. Charge equalization for a series connected battery string is therefore necessary to prevent these phenomena and extend the useful lifetime.

Numerous charge balancing algorithms and circuits have been developed [1], [4]-[7] and well summarized [2], [3]. For a small number of cells, some interesting results have been achieved; for example, automatic equalization based on a multiwinding transformer [5], intelligent cell balance with an individual dc-dc converter [6], and bidirectional equalization with a bidirectional dc-dc converter [4] or a switched capacitor [1], [7]. However, based on the fact that approximately eighty or more batteries are stacked in series to obtain a DC source of more than 300 V in an automotive application [1], [5], the application of the above approaches directly tends to produce difficult problems such as the difficulty of implementing a multiwinding transformer, the prolonged equalization time caused by a cell-to-cell energy shift, the complexity of controlling a large number of bidirectional dc-dc converters, the bulky size and high implementation cost of applying an individual dc-dc converter to each cell, and the high voltage stress caused by a step-up converter.

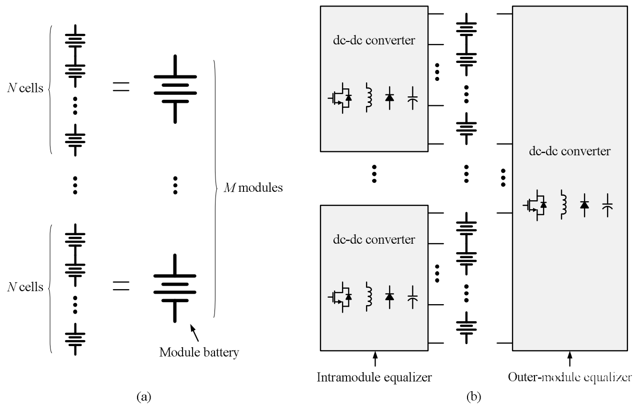


Fig. 1. Concept of battery modularization and design process of a charge equalizer based on the battery modularization.

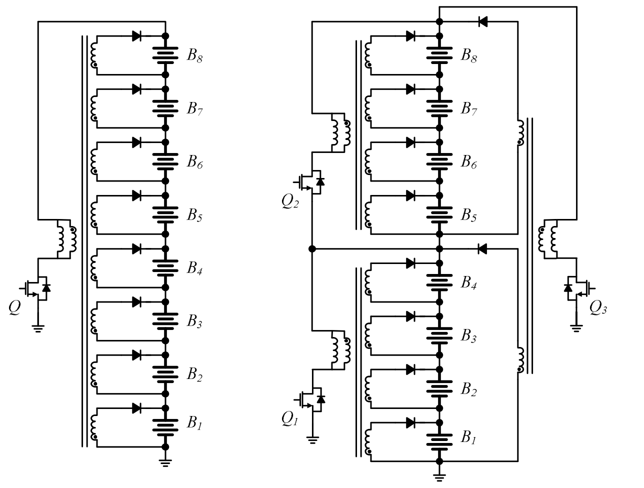
To avoid these problems, this paper proposes a charge equalizer design method based on a battery modularization technique. In this method, a long battery string is divided into several modules. Then, an intramodule equalizer and an outer-module equalizer are designed, respectively. This modularization technique effectively reduces the number of cells; thus, designing the charge equalizer becomes much easier. By applying the conventional charge equalizers, which have been verified already, to the intramodule and the outer-module, we can make the charge equalizer design more flexible. Furthermore, a newly designed equalization circuit can show the advantages that the original one had and can overcome the disadvantages that the original one couldn't remove. Several examples and experimental results are presented to demonstrate the usefulness of this equalizer design method.

2. Proposed Charge Equalizer Design Method

2.1 Battery Modularization

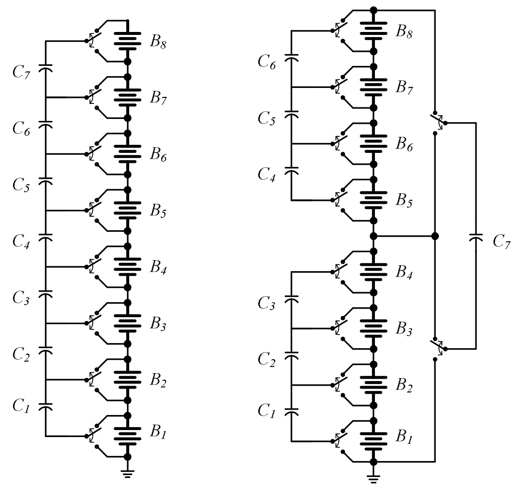
Figure 1 shows the concept of battery modularization and the conceptual design process of a charge equalizer based on the battery modularization. Figure 1(a) shows a modularized battery structure. The whole battery string is grouped into $M*N$ cells, where M is the number of modules and N is the number of cells in each module. This process is called battery modularization. In this configuration, N intramodule equalizers are used to achieve intramodule balance as the conventional case. And an outer-module equalizer of only one is added for outer-module equalization because in the modularized structure the module battery is regarded as another high voltage battery.

For a high number of batteries especially in an HEV, the charge equalizer design is not easy because it has many problems to be solved; e.g., implementation possibility, equalization speed, equalization efficiency, controller complexity, circuit size and cost, voltage and current stress, and so on. However, by using this modularization concept, we can make the charge equalizer design very easy. Figure 1(b) shows the concept of the proposed charge equalizer design method based on the battery modularization.



(a) (b)

Fig. 2. Configuration comparison of a multiwinding transformer based equalizer. (a) Conventional method. (b) Proposed method.



(a) (b)

Fig. 3. Configuration comparison of a switched capacitor based equalizer. (a) Conventional method. (b) Proposed method.

Before applying the modularization concept, an original design problem should be solved for *M**N* cells. However, after applying this concept, that problem can be solved only for *M* modules and *N* cells. The number of cells is significantly reduced. Therefore, the charge equalizer design problem is changed to be easy. Furthermore, because the previous charge balancing approaches can be applied to the intramodule and the outer-module, the equalizer design becomes more flexible.

2.1 Charge Equalizer Design Examples

In this subsection, the proposed equalizer design method based on battery modularization is described. For easy explanation, this scheme is applied to eight cells. They are modularized into 2*4 cells, where two is the number of modules and four is the number of cells in each module. Figure 2(a) shows a conventional configuration when a multiwinding transformer based equalizer is used. In this equalizer, automatic charge balance can be obtained by driving the primary MOSFET switch. Low implementation cost is the advantage of this work. The detail operational principles and its design guides are well described in [5], where the technique to obtain uniform leakage inductors at the secondary side is presented too. However, for a high number of cells, approximately eighty or more cells, the implementation problem and the mismatched leakage inductor problem tend to arise. Moreover, this mismatched leakage inductors causes charge imbalance by itself.

To avoid these problems, a modularized charge equalizer is presented in Fig. 2(b), where eight cells are considered. The multiwinding transformer approach is applied to both the intramodule equalizer and the outer-module equalizer. As shown in Fig. 2(b), the implementation difficulty can be effectively removed and the chance that mismatched leakage inductors appear can be minimized.

For a high number of cells, the usefulness of this modularized equalizer design method is more evident. For example, assume that the number of cells is eighty and that these eighty cells are grouped into eight modules. In this case, eight transformers with ten secondary windings and one transformer with eight secondary windings need to be implemented. On the other hand, in the conventional approach, one transformer with eighty secondary windings is needed. From an implementation point of view, the proposed approach is more likely applied than the conventional one. In addition, the mismatched leakage inductor problem can be minimized at the proposed approach. However, the proposed modularized design method potentially increases the system cost and size because it employs an additional charge equalizer conceptually. This is the drawback of the proposed method. Therefore, it is desirable that the newly designed charge equalizer should be applied to the system that requires a good cell balancing performance at the sacrifice of cost and size.

Another example of the modularized charge equalizer design is shown in Fig. 3, where a switched capacitor based balancing system is applied. For the sake of consistency, a string of eight cells is considered and they are modularized into two modules as before. The conventional equalizer structure is shown in Fig. 3(a), where the switched capacitor is implemented every two adjacent cells [1], [7]. This switched capacitor system has many advantages as described in [7]. Among them, modular design, no need of a close-loop controller, and extremely low voltage stress are the outstanding merits. However, when the string is lengthy, long equalization time should be taken because equalization current always moves from cell to cell by way of the switched capacitors.

To overcome this drawback, a modularized charge equalizer is proposed. Its circuit diagram is presented in Fig. 3(b). Both the intramodule equalizer and the outer-module equalizer employ the switched capacitor system. In this equalizer, not only cell-to-cell energy shift but also module-to-module energy shift is possible. The operation principles and a design example are well summarized in [7]. Compared with the conventional method, the proposed modularized charge equalizer can transfer a large amount of equalizing energy via the outer-module equalizer. Therefore, the shorter equalization time can be achieved. This will be verified by the experimental results later.

3. Experimental results

To show an improved equalization performance of the proposed modularized charge equalizer, a comparative experimental test was conducted. First, a prototype of the modularized charge equalizer based on the switched capacitor system was implemented as its schematic diagram is presented in Fig. 3(b). In this prototype, two types of switched capacitors were implemented; one is a cell-level switched capacitor for the intramodule and the other is a module-level switched capacitor for the outer-module. For careful comparison, the conventional switched capacitor based equalizer shown in Fig. 3(a) was also implemented. The applied components for this prototype are summarized in Table I.

The experimental environment is as follows. Basically, to ensure fair comparison between the conventional switched capacitor based equalizer and the proposed modularized equalizer, the same

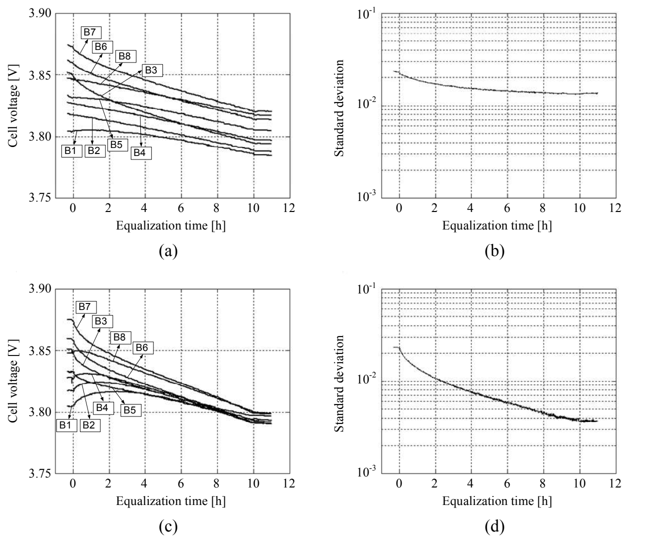


Fig. 4. Equalization performance comparison. (a) Equalization test of the convectional approach. (b) Standard deviation of the convectional approach. (c) Equalization test of the modularized approach. (d) Standard deviation of the modularized approach.

experimental provisions were made. First, the same cell voltage distributions were used at the beginning of equalization. Second, the same pulse-width modulation controller was applied. Third, approximately 10 hours of equalization time and one hour of idle time were consumed evenly. Lastly, all of the cell voltages were monitored every 10 seconds. It is noted that in this experiment, 7 Ah lithium-ion batteries are used.

The comparative experimental results are presented in Fig. 4. Figure 4(a) and 4(b) are for the conventional approach, and Fig. 4(c) and 4(d) are for the modularized approach. As shown in Fig. 4(a) and 4(c), the proposed modularized charge equalizer shows the better equalization performance. At the end of cell balancing process, the maximum cell voltage gap is measured to be about 9 mV, which value is quite small compared with 36 mV of the conventional one. The standard deviations of both the equalization systems were also investigated. As for the conventional one, standard deviation is approximately $10^{-1.95}$, which is similar to the result of the original work at Fig. 9 in [7]. On the other hand, the proposed modularized charge equalizer shows very small standard deviation of about $10^{-2.4}$.

3. Conclusion

In this paper, for a very long battery string of more than approximately 80 cells such as an HEV application, a method of designing a charge equalizer based on a battery modularization technique is proposed. By modularizing the battery string into a small number of groups, the charge equalizer design becomes easy and flexible. In addition, by reusing the conventional charge equalizers which have been verified to be advantageous and outperformed, a newly designed charge equalizer can show the promising equalization performance. The several examples were shown topologically to demonstrate the usefulness of the proposed equalizer deign method. A prototype of a modularized charge equalizer based on a switched capacitor system was implemented. From the comparative experimental results, the proposed modularized equalizer showed the better equalization performance within shorter equalization time compared with the conventional approach. Although the modularized charge equalizer can increase the system size and cost, because the modularized equalizer outweighs these drawbacks this proposed equalizer design method can be widely used for the series connected battery systems such as electric vehicles and HEVs.

TABLE I.
Parameters for the prototype.

Parameters	Description
$B_1 - B_8$	7 Ah Lithium-ion battery
Cell-level balancing MOSFET switches	FDS9431A, P-channel MOSFET, IRF7811A, N-channel MOSFET
Module-level balancing MOSFET switches	IRF5305, P-channel MOSFET, IRFR1205, N-channel MOSFET
Opto-coupler based gate driver	PC900V0NSZXF, PS9661, HCPL-3140,
$C_1 - C_7$	1000μF, 25V, Electrolytic capacitor

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