Thesis for the Degree of Master of Engineering

A Novel Modularized Charge Equalizer for Series Connected Lithium-ion Batteries

by

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직렬 연결 리튬이온 배터리를 위한 새로운 모듈화된 충전 이퀄라이저

Advisor: Prof. Young Seok Jung

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직렬 연결 리튬이온 배터리를 위한 새로운 모듈화된 충전 이컬라이저

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요약

공기오염에 관한 관심의 증가로 자동차의 이산화탄소배출이 주요 원인으로 간주된다. 그러므로 화석 연료를 사용하지 않는 자동차가 유리하고 그 중에서 전기 자동차가 가장 좋은 대안으로 주목받고 있다. 전기 자동차는 충전지에 의해 전원을 공급받는데 특히 다수의 직렬 연결된 배터리 의해서 전원을 공급받는다. 왜냐하면 전압이 필요한 전기자동차 구동열의 필요조건을 만족시키는 것이 일반적으로 단일 배터리 전압 레벨보다 더 높기 때문이다. 최근 리튬 이온 배터리 기술에서의 발전은 많은 장점들을 보여주는데 예를 들면, 높은 파워와 에너지 밀도, 낮은 자가 방전율, 비 메모리 효과 그리고 높은 입력-출력 충전 효율이다. 이러한 장점들 때문에 현재 리튬 이온 배터리는 전기 자동차에 적용되기 위해 연구 중에 있다. 게다가 배터리의 개수가 많아지고 크기가 커질수록 배터리 수명과 배터리 효율을 위한 배터리 관리 시스템(BMS)이 절대적으로 필요하다.

복잡한 전기화학반응 때문에 배터리 성능은 온도 환경, 충전과 방전 방법 그리고 충전상태(SOC)에 매우 민감하다. 실제로 작동 중에 모든 배터리의 조건을 동일하게 만드는 것은 어렵다. 결과적으로 충전 또는 방전 과정 동안 각 배터리를 통해 동일한 전류가 흐를지라도 스택층에서 복원된 배터리의 용량은 같지 않을 것이다. 만약 충전 과정이 적절하게 제어되지 않는다면 일부 배터리들은 작동 사이클의 끝에서 과도하게 방전될 것이다. 이 불균형은 반복적인 충전과 방전을 통해 증가된다.

본 논문의 목적은 직렬 연결 리튬 이온 배터리 스트링의 모듈 세그먼트가 되는 셀 전압 이퀄라이저가 셀 레벨 보다 모듈 레벨에서 적용되게 하는 새로운 접근 방식을 제안하는 것이다. 에너지 컨버터 밸런싱 방법들(벅 또는 부스트 컨버터)과 멀티 스위치드 인덕터 밸런싱 시스템과 비교했을 때 회로에 사용되는 부품 범주가 유사하다. 그러나 제안된 셀 밸런싱 토폴로지의 크기는 좋고 이것의 제어는 다른 능동 배터리 밸런싱 방법들 보다 더 단순하다. 시뮬레이션과 실험결과를 바탕으로 제시된 방법은 인덕터와 변압기의 좋은 효율과 빠른 등화속도를 갖는 장점을 최대한 활용할 뿐만 아니라 우수한 구현과 모 듈화된 충전 이퀄라이저에 의한 비용 절감효과를 가진다.

키워드 : 전기자동차, 리튬 이온 배터리, 모듈화된 충전 이퀄라이저

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I. Background Introduction

1.1 Research Motivation

In recent years, due to the global climate change and the abnormal rising international crude oil prices, sustainable development for environment protection and discovery of clean and green energy are essential. The main air pollution emission not only from industrial manufacturing, but also the daily life of the fuel aboard the vehicle, its engine emissions are one of the major sources of pollution. Especially carbon dioxide is the culprit causing greenhouse effect, the destruction of the ecological environment is very large. Relative to the traditional gasoline powered vehicles, the electric vehicles (EVs) is the important alternative and they have become the research spotlight, it can satisfy these requirements which to aggrandizing eco-friendly, energy-efficient and low pollution. The battery used in electric vehicles must have high energy density, long cycle life, no memory effect and the ability to provide instant high-power, high current and other characteristics. According to recent researches, compared with other commonly used batteries, Lithium-ion battery can provide many advantages such as compact volume, lower weight, higher safety, without memory effect, longer life cycle, higher discharge current, large capacity, and recyclable. In addition, the battery numbers and size ever-going, in order to the efficiency of the battery and battery life, the battery management system (BMS) is absolutely necessary. Battery management system not only can monitor and manage vehicle batteries, but also to provide early warning protection [1]-[4].

As a result of complicated electrochemical reactions, battery performance is very sensitive to the environmental temperature, the charging or discharge profile, and the state of charge (SOC). In practice, it's difficult to make all conditions identical for all the batteries under operation. Consequently, the restored capacities of the batteries in a bank may not be the same during the charge or discharge process even though the same current flows through each battery. The ends of the charging and discharging processes become indefinite due to imbalance among the batteries. If the charging process is not well controlled, some batteries may be excessively refilled while others may not be charged sufficiently. On the other hand, some batteries may be excessively discharged at the end of an operating cycle. The imbalance tends to be magnified through repeated charging and discharging [3].

For the sake of prolonging the battery cycle life and improve charging efficiency, it is recommended that all batteries in the bank should be equally charged before ending the charging process. Quite a lot of cell balancing methods have been proposed, it can be classified into passive balancing method and active balancing method.

The proposed paper is to introduce a appropriate approach for a cell-voltage equalizer, which is applied at the module level rather than at the cell level, being a module segment of the series-connected Li-ion battery string, and energy transfer from higher voltage cells to the battery cell stack directly. Comparing with energy converter balancing methods(buck or/and boost converter) and muti switched inductor balancing system, the balance results rely on only one inductor in the proposed circuit, so the implementation is potentially simpler than exiting balancing circuits.

1.2 Battery Management System

Battery technology has come a long way since the invention of the first voltaic cell in the 1800s. Because of the increased interest in hybrid vehicles, a Battery Management System (BMS) has become one of the chief components in an automobile.

There are three terms apply to the implementation of monitor and control functions in the energy chain. These terms are battery management, power management and energy management [24]. As a rough indication, Power management involves the implementation of functions that ensure a proper distribution of power through the system and minimum power consumption by each system part. Examples are active hardware and software design changes for minimizing power consumption, such as reducing clock rates in digital system parts and powering down system parts that are not in use. Energy management involves implementing functions that ensure that energy conversions in a system are made as efficient as possible. It also involves handling the storage of energy in a system. An example is applying zero-voltage and zero-current switching to reduce switching losses in a switched mode power supply (SMPS). This increases the efficiency of energy transfer from the mains to the battery. Battery management involves implementing functions are multifaceted. Examples of such functions are that monitoring the conditions of individual cells which make up the battery, and the discharge of the battery to prevent damage inflicted on the battery by interrupting the discharge current when the battery is empty, maintaining all the cells within their operating limits, protecting the cells from out-of-tolerance conditions, compensating for any imbalances in cell parameters within the battery chain, providing information about the State of Charge (SOC) and use the determined value to control charging and discharging of the battery and signal the value to the user of the device, State of Health (SOH), and Remaining Useful Life (RUL) of the battery, power the load with a minimum supply voltage, irrespective of the battery voltage, using DC/DC conversion to achieve a longer run time of the device, providing the optimum charging algorithm for charging the cells, responding to changes in the vehicle operating mode and so on [6].

Due to their great energy density, high nominal voltage, and lack of memory effect, Li-ion cells play a more crucial role in electric vehicle (EV) applications. Unfortunately, if not correctly handled, this chemistry can quickly bring loss in performance and produce potentially dangerous situations. Therefore, battery management systems (BMSs) are a practical way to manage these battery packs and improve their efficiency.

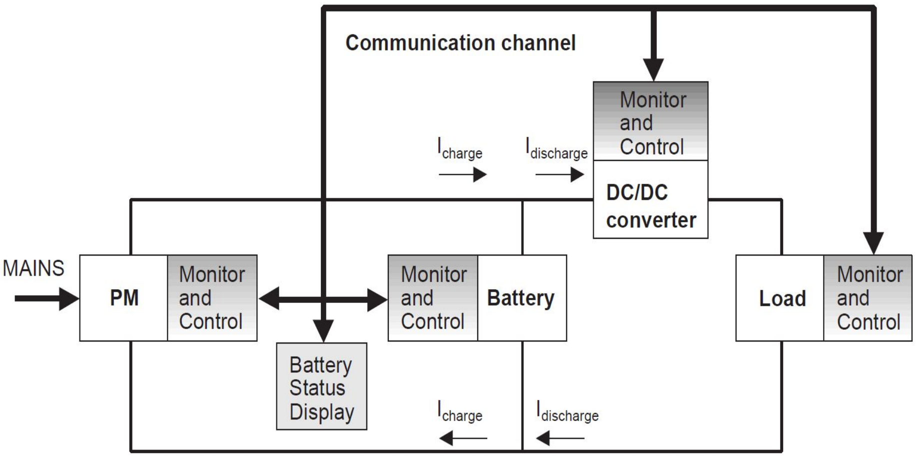


Fig. 1.1 A general Battery Management System (BMS)

1.3 Imbalance of Cells

Imbalance of cells in battery systems is pretty common and significant matter in the battery system life. Because without the balancing system, for instance, cell equalization, the energy storage capacity severely decreases, and the individual cell voltages will drift apart over time and in the worst case, there may be an explosion or fire. The capacity of the total pack will also decrease more quickly during operation then fail the battery system. The cell imbalance falls into two major categories according to [7], they are internal and external sources. Internal sources include manufacturing variance in charge storage volume, variations in internal impedance and differences in self-discharge rate. While the external sources are mainly caused by some multi-rank pack protection ICs, which drain charge unequally from the different series ranks in the pack. In addition the thermal difference across the pack results in varying self discharge rates of the cells.

1.4 Conventional Methods Review

Many systems have been developed in order to equalize the charge among the different cells of battery packs [8-10], usually Balancing methods can be classified into three main groups: battery selection (building the battery pack by selecting the cells with similar properties), passive methods (no active control is used to balance) and active methods (external circuitry with active control is used to balance), as shown in Fig. 1.2.

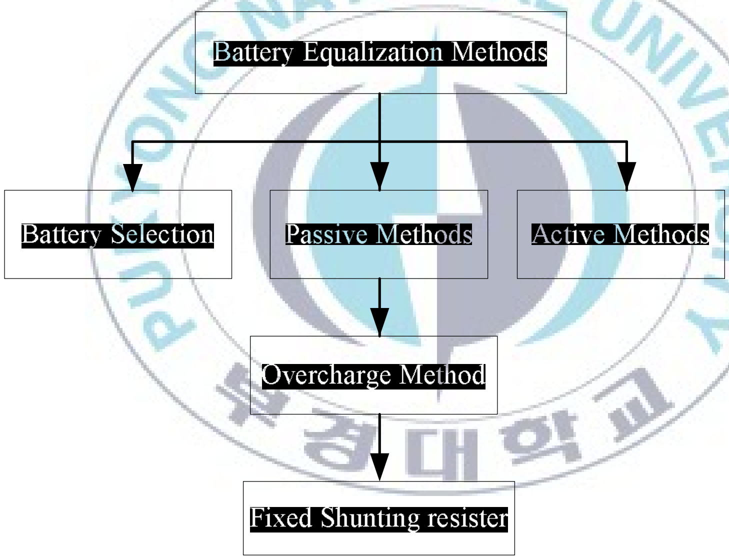


Fig. 1.2 Classification of the battery equalization methods

The passive balancing methods removing the excess charge from the fully charged cell(s) through passive, resistor, element until the charge matches those of the lower cells in the pack or charge reference. Active balancing works by redistributing the energy among the cells to equalize, instead of just wasting it in heat as in passive, as Fig. 1.3 shown, using the active element used for storing the energy such as switched capacitors or inductive power electronics converters.

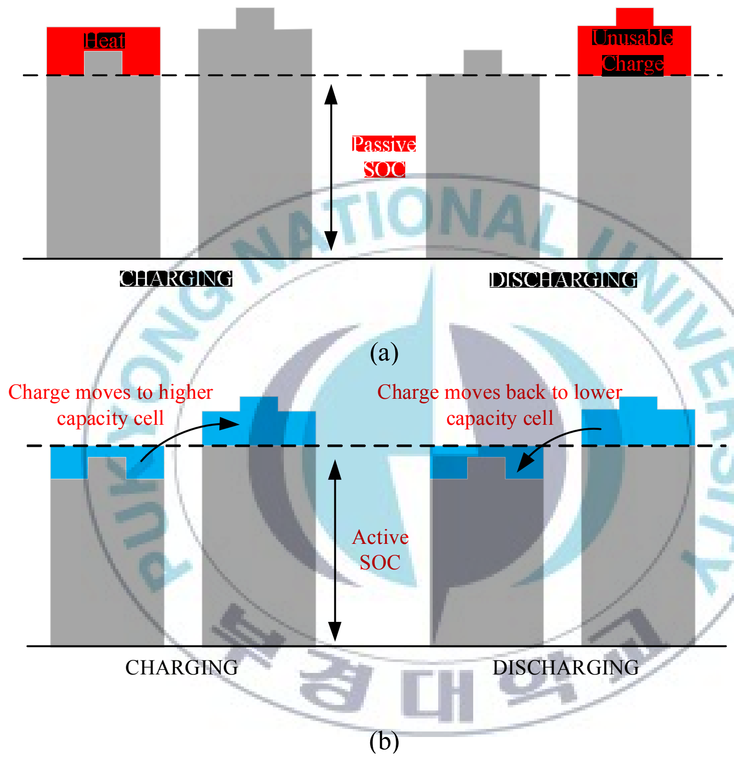


Fig. 1.3 The variance of battery capacity when (a) the passive balancing method (b) the active balancing method

1.4.1 Battery selection

By properly selecting cells so that their properties are uniform (similar electrochemical characteristics) [12, 13] in order to make up the battery pack, the issues of voltage imbalance can be mitigated. Two different screening processes are carried out to select the similar cells. The first one obtains the cells with similar average capacity by discharging at different current regimes. It is based on

$$C_{cell_i} = \int_{t_{SOC=0\%}}^{t_{SOC=100\%}} I_{cell_i} dt \qquad (1)$$

where C_{Celli} is the cell capacity defined as the maximum electrical charge(Ah) that the cell can deliver from the fully charged state to the fully discharged state, I_{Celli} is the cell current, and t_{SOC}=100% and t_{SOC}=0% are the State of Charge of the cell at the fully charged and discharged states, respectively. These condscreening process is applied to the cells selected in the first one. Pulse type discharging/charging currents are applied for different SOC points to select the cells with similar voltage variance (similar series resistance associated with the cell). This method is not enough to keep the series string balanced since their self-discharge can vary differently along their lifetime [14]. It can only be useful in case of complementing a balancing system.

1.4.2 Passive balancing methods

The passive balancing method can be only used for Lead-acid and Nickel based batteries because Lead-acid and Nickel based batteries can be brought into overcharge conditions without permanent cell damage. They can be subdivided into two subgroups: overcharge and shunting resistor balancing, as shown in Fig. 1.4. When the overcharge is not very severe, the excess energy is released by increased cell body temperature. When the overcharge is too much, the energy will be released by gassing via the gassing valve equipped on the cells. This is the natural method of balancing a series string of such cells. However, overcharge balancing is only effective on a small number of series cells because balancing problems grow exponentially with the number of series cells. The fixed shunting resistor method uses a resistor in parallel with each individual cell in the pack, and the current is partially or totally bypassed from the cells in order to limit the cells voltages. This method is continuously bypassing current and therefore continuously wasting energy [15].

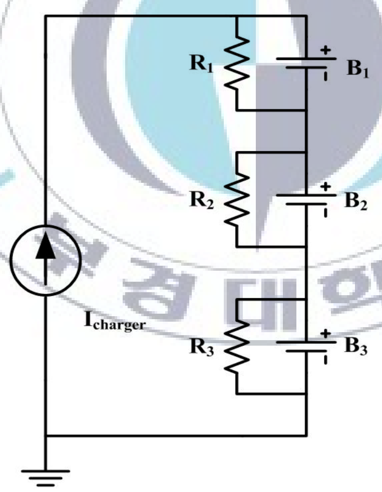


Fig. 1.4 Fixed shunting resistor balancing method

1.4.3 Active balancing methods

The active balancing method can be used for most modern battery systems because they do not rely on the characteristic of cells for balancing. This method is the only applicable balancing method for Lithium based batteries since the temperature of the Lithium based batteries must be rigorously controlled in the safety operation range. Generally, active balancing method should be used for Lithium-ion battery pack which has three cells and up in series connected [11].

Many active balancing methods are available. Sorted by energy flow, active balancing methods can be grouped into four big categories. They are dissipative method (cell pass), single cell to pack method (cell to pack), pack to single cell method (pack to cell) and single cell to single cell method (cell to cell) [15]. A diagram of the different active balancing methods is shown in Fig. 1.5.

In cell bypass methods, cells currents are bypassed when the cells voltages reach their upper limit. Two groups subdivide this method: shunt resistor and shunt transistor methods.

a. Shunt resistor method

It is as shown in Fig. 1.6 (a), switched shunt resistor is based on removing the energy from the higher cell(s) not continuously but in a controlled way using switches/relays. It could work in two modes. First, the continuous mode, where all relays are controlled by the same on/off signal. Second, detecting mode, where the cells voltages are monitored. When the imbalance conditions are sensed, it decides which resistor should be shunted. This method is more efficient than the fixed resistor method, simple, reliable and can be used for the Li-Ion batteries. The main drawback in these methods the excess energy from the higher cell(s) is dissipated as heat, there is a need for thermal management, and if applied during discharge will shorten the battery's run time [5].

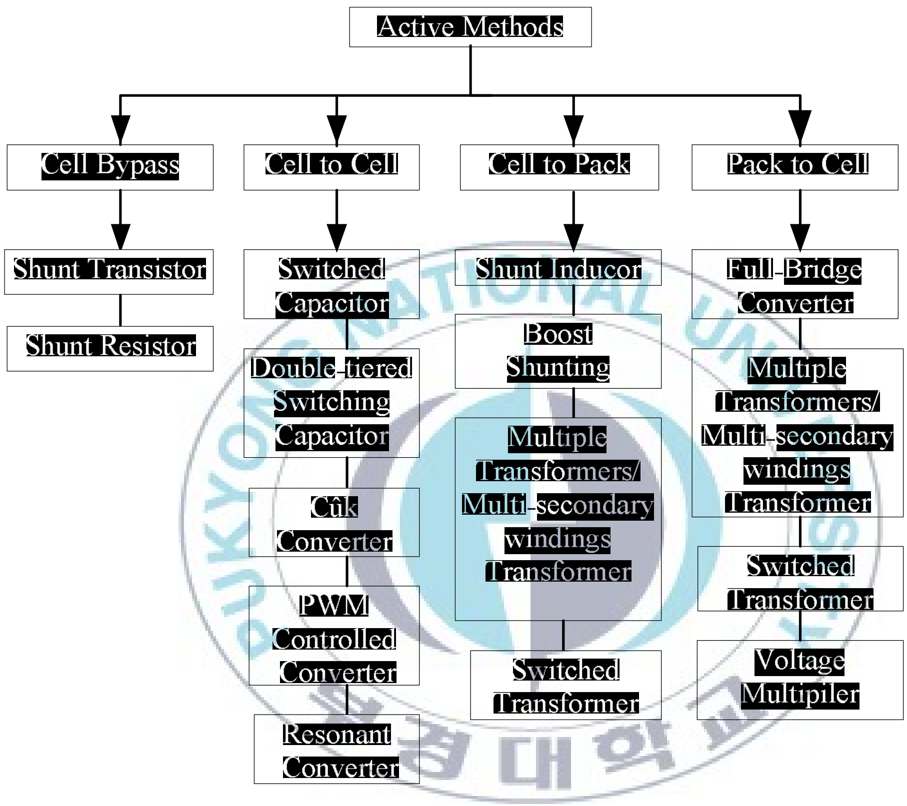
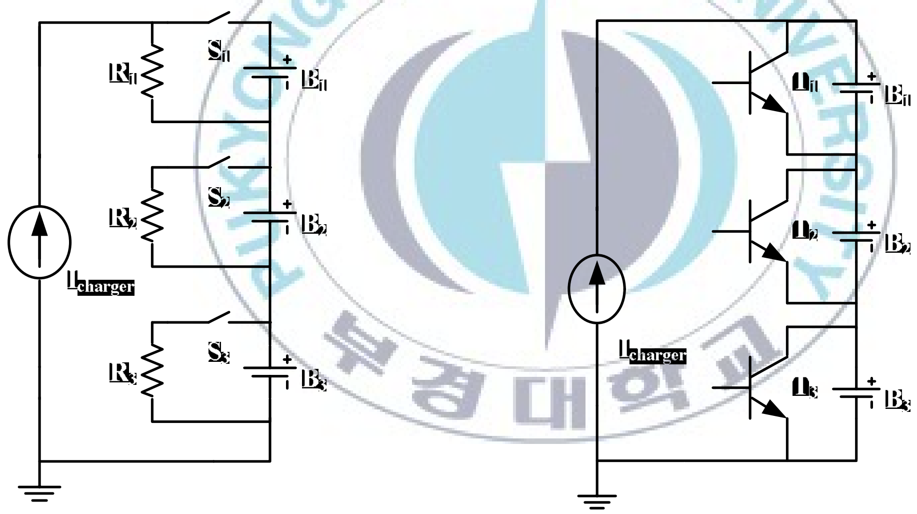


Fig. 1.5 Classification of the different active balancing methods

b. Shunt transistor method

It is as shown in Fig. 1.6 (b), It shares the same idea as the shunt resistor method. A transistor is set in parallel with each individual cell. During charging, when the cell reaches the maximum voltage, the current is proportionally bypassed around the cell and so this cell is charged at constant voltage. In this method, the current is only shunted at the end of the charging process, so compared to shunt resistor working in the first mode, it has less energy loss. Compared to shunt resistor working in the second mode, it does not need intelligent control, and therefore the cost is lower.

Cell to cell methods transfer the extra energy stored in the most charged cells to the adjacent least charged ones. This method can be subdivided into five methods, the switched capacitor, the double-tiered switching capacitor, the Cûk converter, the PWM (Pulse Width Modulation) controlled converter and the Quasi-Resonant and the resonant converter ones.



(a) (b)

Fig. 1.6 Cell bypass method (a) Shunt resister (b) Shunt transistor

c. Switched capacitor method

In this method is shown in Fig. 1.7(a). As illustrated it requires n-1 capacitors and 2n switches to balance n cells. Its control strategy is simple because it has only two states. In addition, it does not need intelligent control and it can work in both recharging and discharging operation. The disadvantage of the switched capacitor topology is its relatively long equalization time [5].

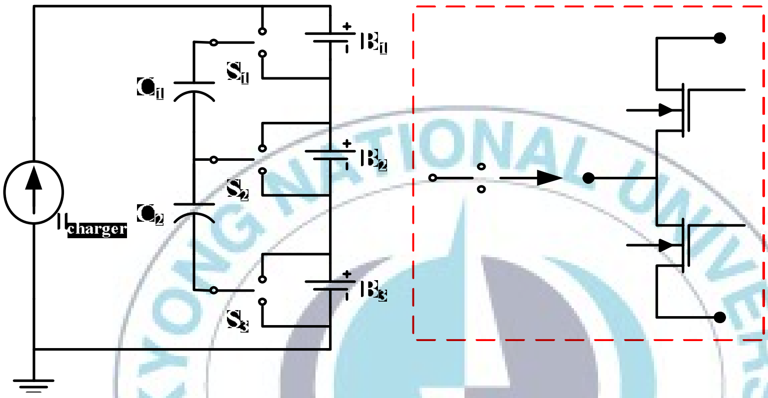


Fig. 1.7 Cell to cell method (a) Switched capacitor

e. Double-tiered switching capacitor method

Double-tiered switched capacitor balancing method is also a derivation of the switched capacitor method, the difference is that it uses two capacitor tiers for energy shuttling as shown Fig. 1.7(b). It needs n capacitors and 2n switches to balance n cells. The advantage of double-tiered switched capacitor is that the second capacitor tier reduces the balancing time to a quarter of the time needed for the switched capacitor method. The disadvantages are higher cost and size. In addition, the capacitor-based topologies can work in both recharging and discharging operation.

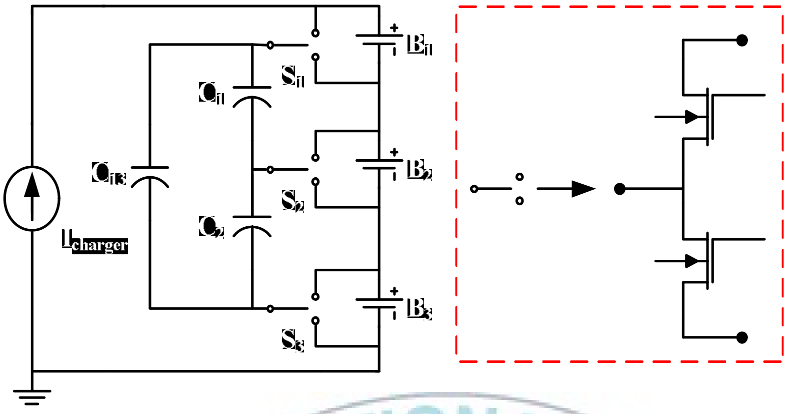


Fig. 1.7 Cell to cell method (b) Double-tiered switching capacitor

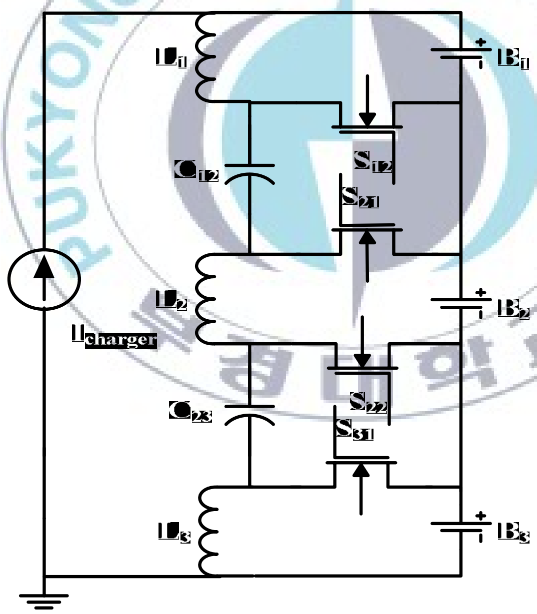


Fig. 1.7 Cell to cell method (c) Cûk converter

f. Cûk converter method

The topology of this method is shown in Fig. 1.7(c). It requires n−1 individual cell equalizer (ICE) circuit to balancing n cells. Each ICE circuit has two inductors, two switches and one capacitor. The main advantage of this method is that it can be utilized in high power applications, but its main disadvantage is its control complexity.

g. PWM controlled converter method

The basic topology is shown in Fig. 1.7(d). Every module for equalization is connected across each two adjacent cells to allow next-to-next energy transfer from the cell with the highest voltage to the cell with the lowest voltage [25]. The energy is firstly transferred from the highest voltage cell to the inductance where it is stored, and then the inductance discharges the energy to the lowest voltage cell. The energy transfer and the flow direction are carried out by adjusting the duty cycle of the corresponding transistors, which are activated with a PWM signal. This method is good for high power applications, but its control complexity.

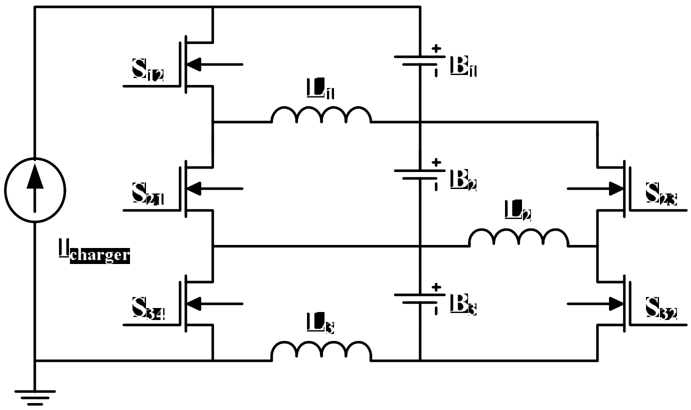


Fig. 1.7 Cell to cell method (d) PWM controller converter

h. Quasi-Resonant/resonant converter method

The quasi-resonant converter shown in Fig. 1.7(e), can be either zero-current quasi-resonant (ZCQR) or zero-voltage quasi-resonant (ZVQR) converters. Instead of using intelligent control to generate a PWM signal, resonance circuits are used for both transferring energy and driving the switches. Lr and Cr are constructed as the resonant tank to achieve the zero current switching function for the symmetrical and bi-directional battery equalizer. The main advantage of the resonant converters is that they can reduce the switching losses thus increasing the balancing system efficiency. Unfortunately, the resonant converters have a very complex control, difficult implementation, as well high converter cost.

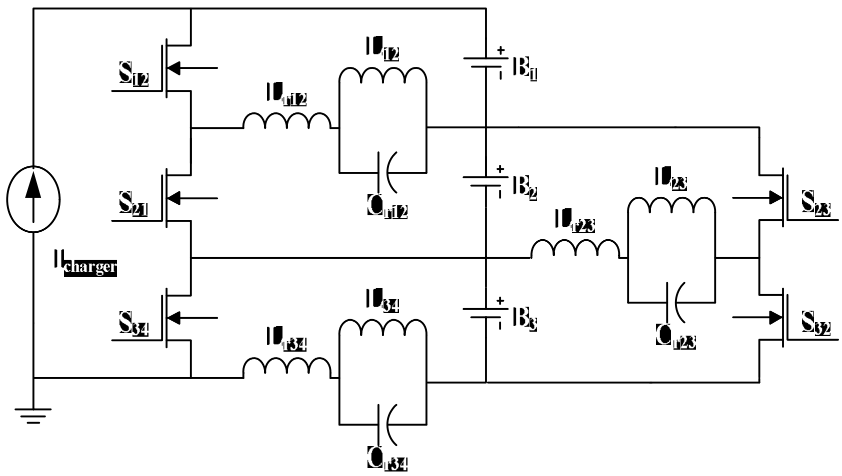


Fig. 1.7 Cell to cell method (e) Quasi Resonant converter method

Cell to pack methods transfer the energy from the highest voltage cell to the whole battery pack, pack to cell methods transfer the energy from the whole battery pack to a single cell, by means of galvanic isolated DC/DC converters. This method can be subdivided into five methods: the shunt inductor, boost shunting, multiple transformers, multi secondary windings transformer, and switched transformer ones.

i. Shunt inductor method

The configuration of this method is shown in Fig. 1.8(a). In case a cell is detected to have a higher voltage than the other ones of the pack, the inductor is alternately set in parallel with the cell (the cell is shunted by the inductor), activating the corresponding switches of the cell, and with the whole pack, activating the switches Sa and Sb in the figure, with the aim of transferring the extra energy from the imbalanced cell to the pack. This method is good for high power applications, but it is very slow since only one cell is being balanced at every instant.

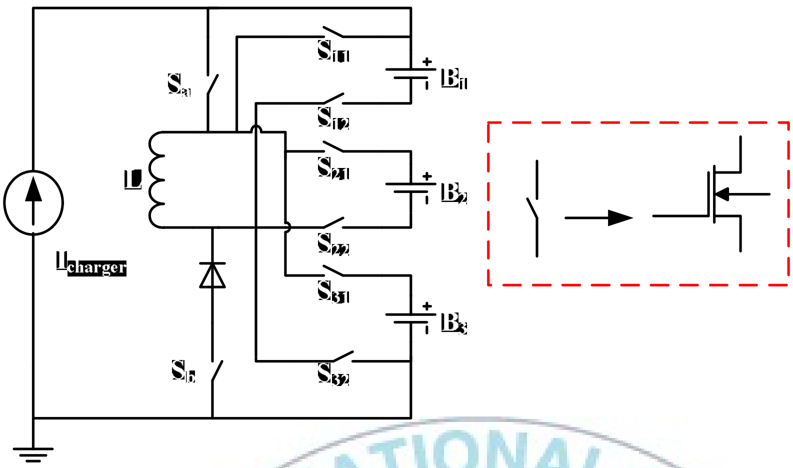


Fig. 1.8 Cell to pack method (a) Shunt inductor

j. Boost shunting method

Boost converter used for removing the excess energy from a single cell to the total pack. The topology of this method is shown in Fig. 1.8(b). The voltage sensing of cell as well as an intelligent controller are needed for the converters operation. Converters balancing methods are relatively expensive and complex but they are used for modular design with their high efficiency.

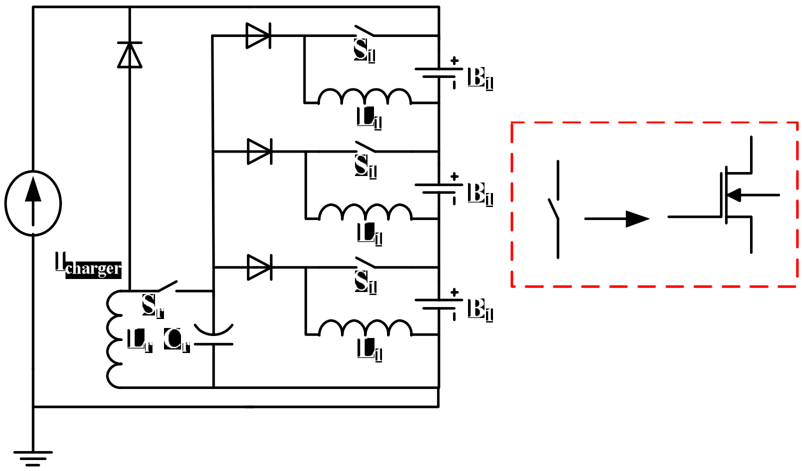


Fig. 1.8 Cell to pack method (b) Boost shunting

k. Multiple transformers and Multi secondary windings transformer method

The multi secondary windings transformer “shared transformer” topology has a single magnetic core with one primary winding and multiple secondary windings one for each cell. The circuit is complex and the cost is high, there is also the saturation problem. Compared to the multi secondary windings transformer scheme, this method is better for modular design and battery pack extension without changing the magnetic core, while it is still expensive.

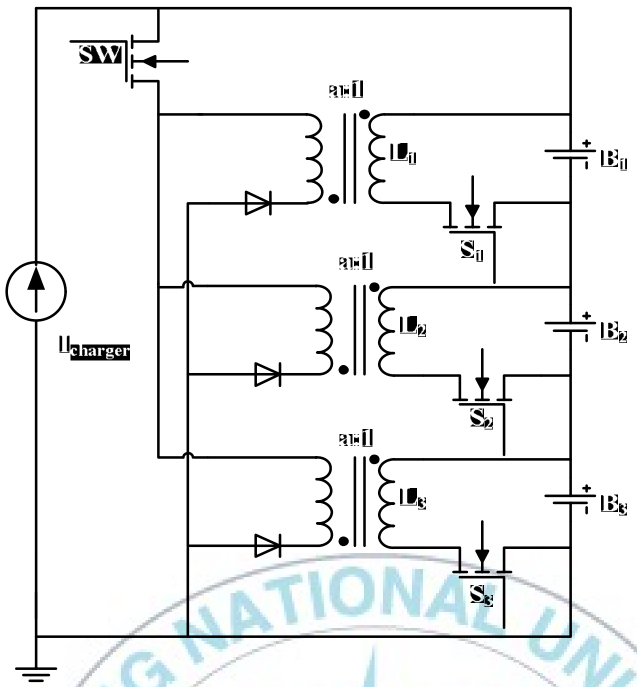


Fig. 1.8 Cell to pack method (c) Multiple transformers

L. Switched transformer method

The single winding transformer (SWT) as well, known as "switched transformer, ST" shown in Fig. 1.8(e). This method has two techniques for cell balancing. First technique "pack-to-cell topology" is based on carrying the energy from the whole battery pack through the switching transformer and transferring that energy to the weak cell(s) using the corresponding switch(s). The second technique "cell-to-pack topology" is based on transferring the energy from the high energy cell(s) through the transformer into the battery pack. This method can be utilized in high power applications, but its cost, size, and control complexity are high, and in addition it is relatively slow.

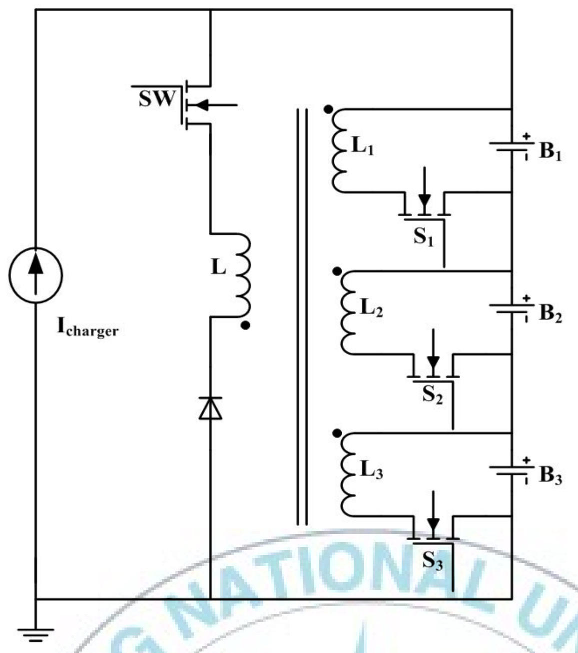


Fig. 1.8 Cell to pack method (d) Multi secondary windings transformer

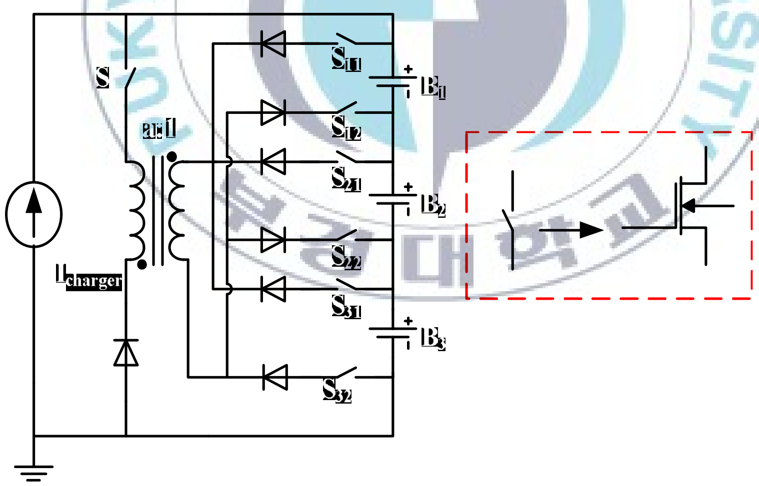


Fig. 1.8 Cell to pack method (e) Switched transformer

Finally, cell to pack to cell methods transfer the energy from the set cell(s) to the whole pack, from the whole pack to the target cell(s) or from the set cell(s) to the target cell(s). This method can be subdivided into five methods, the voltage multiplier, full-bridge converter, multiple transformer, multi secondary windings transformer, and switched transformer ones.

m. Voltage multiplier method

In this method, two states are alternated continuously since the switch is controlled by a square signal. In the first state, each cell is being discharged through the even-numbered diodes, and therefore capacitors are being charged. The variations in the cells voltages are small enough to be negligible during a single switching cycle since the capacitors have a very low capacitance. During the off period, the charger current is distributed to the capacitors and through the odd-numbered diodes to the cells, which are charged with more or less current depending on whether the cells are less or more charged with respect to the average voltage. The topology is depicted in Fig. 1.9(a). This balancing method can be utilized in high power applications. Its cost is relatively low and its efficiency can be high if the switching frequency is high enough to reduce R, and the utilized cells have a voltage high enough to neglect the forward voltage drop of the diodes.

n. Full-bridge converter method

This method is as shown in Fig. 1.9(b). They can be used as a AC/DC converter, which is suitable for plug-in or as a DC/DC converter. Energy is transferred from the whole battery pack to the individual cells. The main advantages of this method are the relatively high efficiency, its easy modularity and its suitability for high power applications. Its main disadvantage is its control complexity.

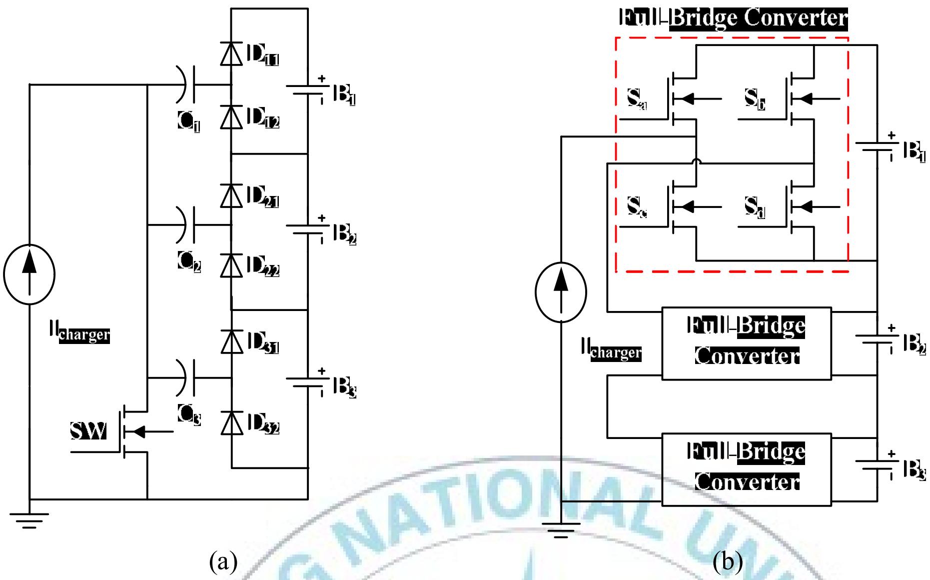


Fig. 1.9 Pack to cell method (a) Voltage multiplier (b) Full-bridge converter

II. Lithium batteries

2.1 Historical Overview

Batteries have been around for a long time. Earthen containers that served as galvanic cells dating from 250 BC have been found in Baghdad [16]. These containers were filled with iron and copper electrodes, together with an organic acidic solution. This yielded a cell capable of supplying 250 mA at a voltage of 0.25 V for approximately 200 hours. These cells were used to gild silver. Two names are closely associated with the development of batteries and the related science of electrochemistry. These names are Luigi Galvani and Alessandro Volta [17]. Galvani performed an experiment in 1790, in which he suspended a frog from an iron hook. With a copper probe he measured electric pulses, which he believed originated in contractions of the muscles of the frog's legs. Volta attributed these contractions to the current flowing between the iron and copper metals. To prove that current could flow between two metals with an electrolyte in between, he built a 'pile' consisting of alternating silver and zinc plates interleaved with paper or cloth, which was soaked with an electrolyte. Hence, Volta was the first person in modern times to have built an actual battery. He patented this structure in 1800. In 1834, Michael Faraday derived the laws of electrochemistry based on Volta's work. This established a connection between chemical and electrical energy.

In addition to the types of batteries mentioned so far, a wide variety of batteries have been developed since Volta's 'pile', both rechargeable and non-rechargeable. The advances in the development of portable electronic systems have had a significant effect on the development of new types of batteries. However, only fairly little progress have been made in improving battery characteristics such as energy density, shelf life and reliability in comparison to the advances made in electronic circuits [18]. While existing types of batteries are continuously being improved, new types keep appearing. The introduction of the nickel-metal hydride (NiMH) battery in 1990 and the lithium-ion (Li-ion) battery in 1991 were of a great importance for portable consumer products. Research at Royal Philips Electronics played an important role in the development of NiMH batteries [6],[7]. Apart from the continuous need for higher energy densities, environmental concerns have also boosted the development of these new types of batteries.

2.2 Battery Characteristics

A battery's basic task is to store energy obtained from the mains or some other external power source and to release it to the load when needed. This enables a portable device to operate without a connection to any power source other than a battery. Different battery systems with different chemistries and different characteristics exist. Examples of some commonly encountered battery systems are nickel-cadmium (NiCd), nickel-metal-hydride (NiMH) and lithium-ion (Li-ion) batteries. The characteristics of the various battery systems vary considerably, even for batteries with the same chemistry, but, for example, a different design or different additives.

The main characteristics of the most important secondary battery systems are summarized in Table 1 [16], [18], [19], [20]. Ranges are given for the energy density, specific energy, self-discharge rate and cycle life of almost all of the systems in the Table 1, because so many different types of battery systems are available on the market.

Table 1. Overview of the main characteristics of the most important secondary battery systems

Battery system	NiCd	NiMH	Li-ion	Li-ion polymer	SLA	Recharge -able alkaline
Average operating voltage [V]	1.2	1.2	3.6	3.6	2.0	1.5
Energy density[Wh/l]	90..150	160..310	200..280	200..250	70..90	250
Specific energy[Wh/kg]	30..60	50..90	90..115	100..110	20..40	20..85
Self-discharge rate [%/month] at 20℃	10..20	20..30	5..10	1	4..8	0.2
Cycle life	300..700	300..600	500..1000	200	200..500	15..25
Temperature range [℃]	-20..50	-20..50	-20..50	-20..60	-30..60	-30..50

NiCd batteries

The positive nickel electrode is a nickel hydroxide/nickel oxyhydroxide (Ni(OH)2/NiOOH) compound, while the negative cadmium electrode consists of metallic cadmium (Cd) and cadmium hydroxide (Cd(OH)2). It is possible to charge NiCd batteries in a relatively short period of time because of their robustness. Charge times of only 10 minutes have been reported [16]. The average cell voltage is 1.2 V. The characteristics of high power delivery and short recharge times make NiCd batteries very popular for power tools. Nevertheless, NiCd batteries have some drawbacks. First of all, their energy density and specific energy are relatively low. Secondly, NiCd batteries suffer from the so-called memory effect [16],[18],[20]. This effect can be defined as a decline in effective capacity with repeated partial charge/discharge cycles. As a final drawback, the use of cadmium in NiCd batteries involves serious environmental problems.

NiMH batteries

Table 1 illustrates that NiMH batteries offer the same average operating voltage as NiCd batteries, with the great advantage of a higher energy density. In NiMH batteries a metal-hydride (MH) alloy has replaced the cadmium electrode. The positive electrode and the electrolyte are more or less the same as in NiCd batteries. Although the chemistry of a NiMH battery is similar to that of a NiCd battery, there are differences between the two:

Due to the fact that the MH electrode has a higher energy density than the Cd electrode in NiCd batteries, NiMH batteries have a better energy density than NiCd batteries [21].

One of the factors that influence the self-discharge rate of a NiMH battery is the ability of the MH electrode to retain the stored hydrogen under storage conditions. So The self-discharge rate of NiMH batteries is somewhat higher than that of NiCd batteries.

A difference between the charging process of NiMH batteries and that of NiCd batteries is that the net charging reaction in a NiMH battery is exothermic. This means that heat is generated continuously during the charging. On the other hand, the net charging reaction of a NiCd battery is endothermic. This means that heat is consumed during the first phase of charging [21].

Li-ion batteries

Li-ion cells offer the advantage of a high average operating cell voltage of 3.6 V, because of the very negative standard potential of lithium with respect to the standard hydrogen reference electrode (SHE). Moreover, Li-ion batteries have a relatively high specific energy, which results in batteries that are lighter than Nibased batteries at the same capacity. The operation of Li-ion batteries is based on the transfer of lithium ions from the positive electrode to the negative electrode during charging and vice versa during discharging. This is generally referred to in the literature as the 'rocking chair' principle [20],[21],[22]. Table 1 shows that, apart from a higher specific energy, Li-ion batteries also have considerably lower self-discharge rates than Ni-based batteries. Moreover, Li-ion batteries do not suffer from the memory effect. Furthermore, Li-ion batteries are less capable of delivering large currents, expressed in C-rate, than Ni-based batteries. Over discharging Li-ion batteries leads to a decrease in cycle life. Without further precautions, overcharging Li-ion batteries leads to dangerous situations and may even cause a fire or an explosion of the battery.

Li-ion-polymer batteries

As a successor of the Li-ion battery with a liquid organic electrolyte, The basic difference with respect to Li-ion batteries is that the electrolyte consists of a solid ion-conducting polymer material [19],[20],[21]. Polymer electrolytes are less reactive with respect to lithium than liquid electrolytes. Li-ion polymer batteries are very lightweight and have improved safety. However, these batteries will cost more to manufacture and have a worse energy density than lithium-ion batteries.

Sealed Lead Acid Batteries (SLA)

SLA batteries contain only a limited amount of electrolyte, which is absorbed in the separator or a gel. The positive electrode of an SLA battery is formed by lead dioxide (PbO2), while metallic lead (Pb) in a high-surface-area porous structure is used for the negative electrode. A sulphuric acid (H2SO4) solution is used for the electrolyte. The average operating voltage of an SLA cell is 2 V. Advantages of the SLA battery are its good rate capability and relatively low self-discharge rate. Moreover, SLA batteries do not suffer from the memory effect. A major disadvantage of SLA batteries is their low energy density and specific energy. An additional disadvantage is the problem of irreversible capacity loss under deep discharge conditions.

Rechargeable alkaline batteries

The average operating voltage of a rechargeable alkaline cell during practical use is 1.3 V. The rechargeable alkaline battery offers the advantage of a low self-discharge rate and low cost. Disadvantages are the poor cycle life and the fact that the initial capacity is lower than that of primary alkaline batteries.

2.3 Battery Safety Operation

Compared with other commonly used batteries, lithium-ion batteries are featured by high energy density, high power density, long life and environmental friendliness and thus have found wide application in the area of consumer electronics. However, automotive lithium-ion batteries have high capacity and large serial-parallel numbers, which, coupled with such problems as safety, durability, uniformity and cost, imposes limitations on the wide application of lithium-ion batteries in the vehicle. The battery voltage, current and temperature have to be monitored and the safety switch has to be controlled to ensure that the battery is never operated in an unsafe region. The reason for this is that battery suppliers are particularly concerned with safety issues due to liability risks. A voltage range, a maximum current and a maximum temperature determine the region within which it is considered safe to use a battery. Generally speaking, in the higher voltage range these processes may eventually lead to a fire or an explosion, whereas in the lower voltage range, they lead to irreversible capacity loss of the battery. The maximum voltage is dictated by two factors, the maximum battery capacity and its cycle life. The cycle life denotes the number of cycles the battery can be charged and discharged before it is considered to be at the end of its life. A battery's life ends when the capacity drops below a certain level, usually 80% of its nominal capacity. This is illustrated in Figure 2.1, which shows the maximum battery capacity and the cycle life as a function of the voltage applied to the battery during charging. The figure illustrates that the higher this voltage, the higher the maximum battery capacity and the lower the cycle life will be. Around 4.1 to 4.2 V, a 100 mV increase in battery voltage yields a 12% capacity increase, but a sharp decrease in cycle life of 200 cycles.

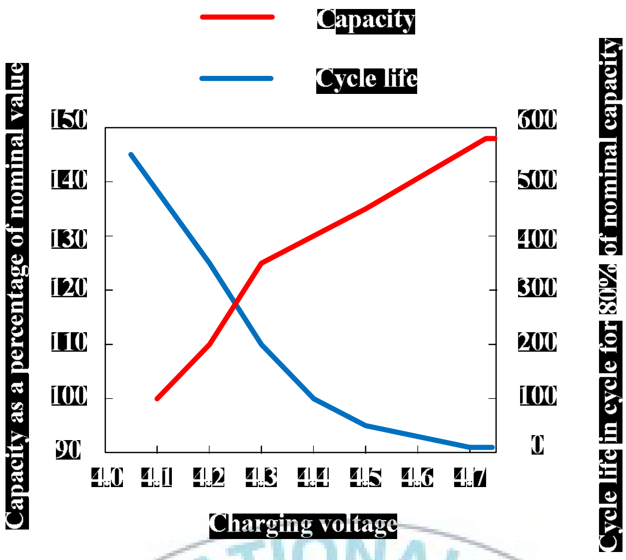


Fig. 2.1 Maximum battery capacity and cycle life as a function of battery voltage for a Li-ion battery

To solve those problems, people try to develop new battery system that could be working under very bad situations, and on the other hand, the current commercial lithium-ion batteries must be fitted with a management system, through which the lithium-ion batteries can be controlled and managed effectively, thus every single cell would be working under proper conditions that those fault described above would not happen which means that every cell should be operated within the lithium-ion battery safety operating window shown in Fig. 2.2, we can obtain that the reliable operating temperatures are: discharging at 20 to 55 ˚C and charging at 0 to 45 ˚C. Usually, the operating voltage of lithium-ion batteries is between 1.5 V and 4.2 V [21].

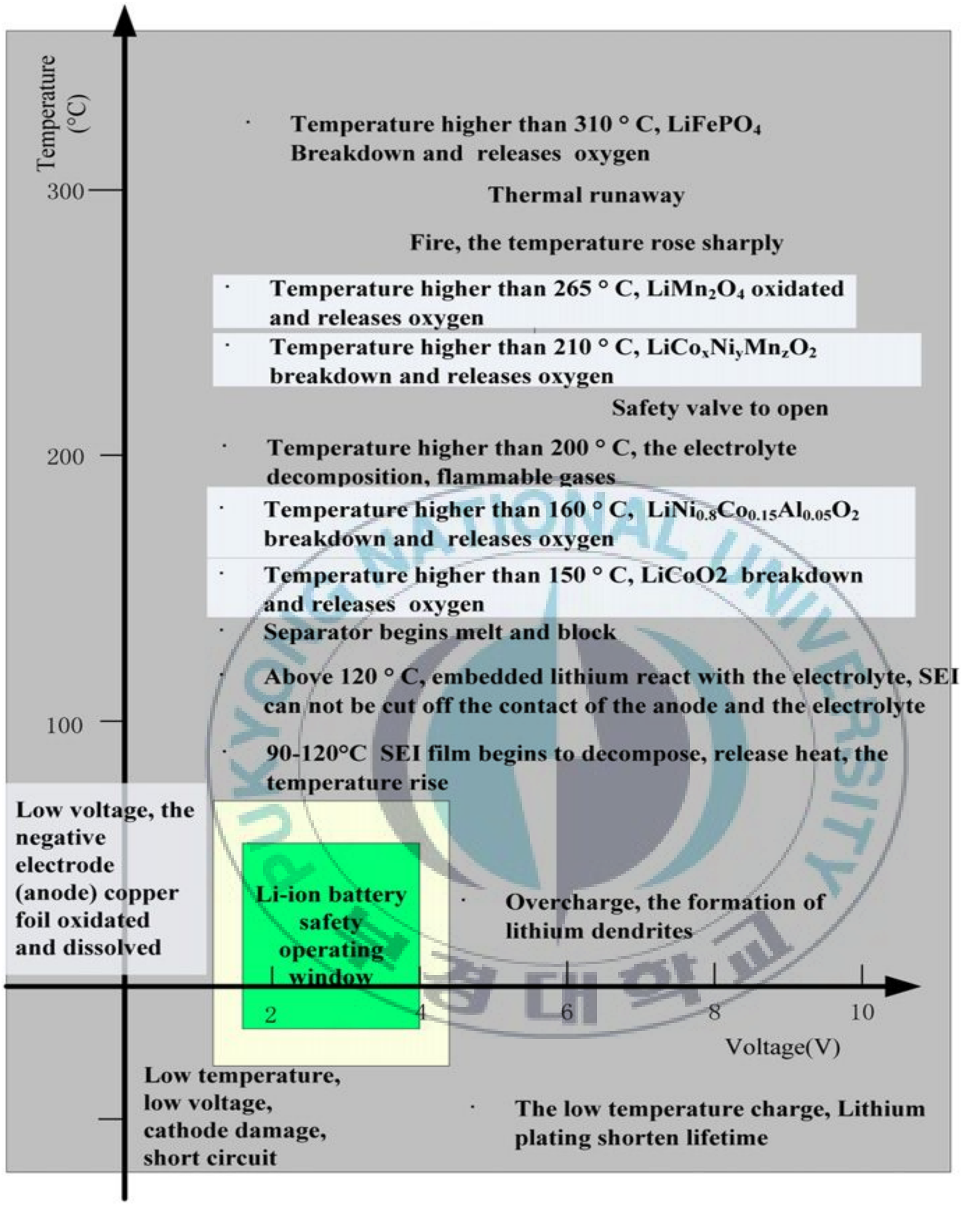


Fig. 2.2 Safety operation window for lithium-ion battery [21]

2.4 Battery Modularization

Series connected battery strings have been widely used for many applications, such as electric vehicles, hybrid electric vehicles (HEVs), electric scooters, and uninterruptible power supplies. Among them, an HEV battery is severely exposed to a charge and discharge environment, because an HEV can recover energy from the wheels during regenerative braking and reuse it to propel the vehicle at low speeds or provide extra power for high acceleration.

Furthermore, this repeated charge and discharge phenomenon causes a cell mismatch problem, because the batteries have inevitable differences in chemical and electrical characteristics from manufacturing; they also experience mismatched ambient temperatures when they are used and accelerate asymmetrical degradation with aging [1][2][8].

The problem is that when these imbalanced batteries are left in use without any control, such as cell equalization, the energy storage capacity severely decreases, and, in the worst case, there may be an explosion or fire. The charge equalization for a series-connected battery string is, therefore, necessary to prevent these phenomena and extend the useful life time.

However, in an electric drive bus with super capacitors as the only on-board power source, 600 cells are used to provide motive power. Every 10 cells are united into one mono block and equalized as a whole. Only after 103 cycles of charging and discharging cycles, over 80 cells detected to be weaker and obtain a dc source of more than 300V [9][22].

For instance, in the non-dissipative charge-balancing method, problems include the difficulty of implementing a multi-winding 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.

To avoid these problems, we propose a charge equalizer design method based on a battery modularization technique. This modularization technique effectively reduces the number of cells that we take into account when designing a charge equalizer. Consequently, the design of the charge equalizer becomes more easier and flexible.

2.5 Electronic Safety Switch

Making the right choice of device is an important issue in order to minimize losses and to guarantee the system works. The BJT is not currently popular in electronic systems, it is preferred in current amplifiers, and the difficult choice is between MOSFET and IGBT. The choice depends on the switching frequency, voltage and power level.

According to the specifications of the most commonly available switches, the largest power capabilities are in the diode and thyristor, while in terms of speed the MOSFET has the fastest switching frequency [23]. At a switching frequency of 20 kHz, the IGBT can be seen as a good device, but the MOSFET can work at this frequency as well. The IGBT has low conduction losses, but the switching time is high compared to the MOSFET. The MOSFET has replaced others in many applications where high switching frequency is needed, at voltages (> 600-1000 V) the IGBT still preferred, but at high frequency (> 20-100 kHz) the MOSFET is the only device that can be used.

III. Proposed Battery Balance Method

According to the fact that more than 50 batteries are stacked in series for an HEV, each control category can be divided into two parts based on energy transfer type: cell to cell and cell to pack. In case of cell to cell, each cell should have an individual converter to transfer the balancing energy from normal cells to unbalanced cell. This type cannot be directly applied to a large number of battery cells due to an implementation size and cost. Compare to the cell-to-cell type, cell to pack equalization type shows effective balancing performance without an additional modular balancing. It transfers the balancing energy from higher voltage cell to overall batteries.

In this paper, three lithium-ion battery cells employ the modularized concept of the battery string in whole equalization system. With this configuration, the size and cost problem of the battery equalizer is effectively solved and the individual equalization performance can be easily satisfied.

3.1 Basic Information on Batteries Balance Circuit

We proposed the battery balancing circuit is shown in Fig. 3.1. Due to for each battery cell has the same circuit parameters are applied, so the total circuit can be divided into M battery modules, respectively, call them M_1, M_2, …, M_N, which corresponds to each battery cell.

To extract M_1 form the circuit. Because the remaining battery modules are identical to each other and have same components as battery module 1. As

Fig. 3.2 shown, there are four schottky barrier diodes D_{1A}, D_{1B}, D_{1C} and D_{1D} are used in one battery module, L_1 is the only one inductor in the module. S_{1DA} and S_{1DB} as switching device, typically metal–oxide–semi conductor field-effect transistor(MOSFET), P-channel MOSFET S_{1DA} is connected to the positive terminal of the battery, and the N-channel MOSFET S_{1DB} is inserted between the negative terminal of cell B_1 and the inductor.

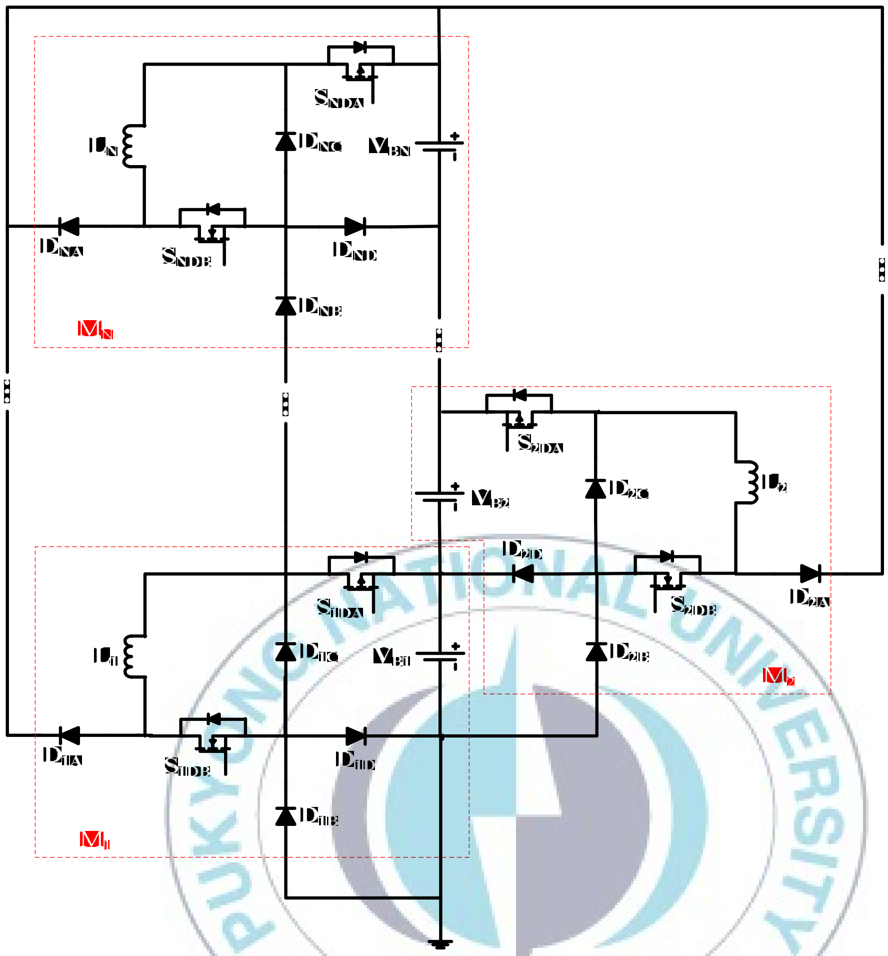


Fig. 3.1 Topology of the proposed balance circuit

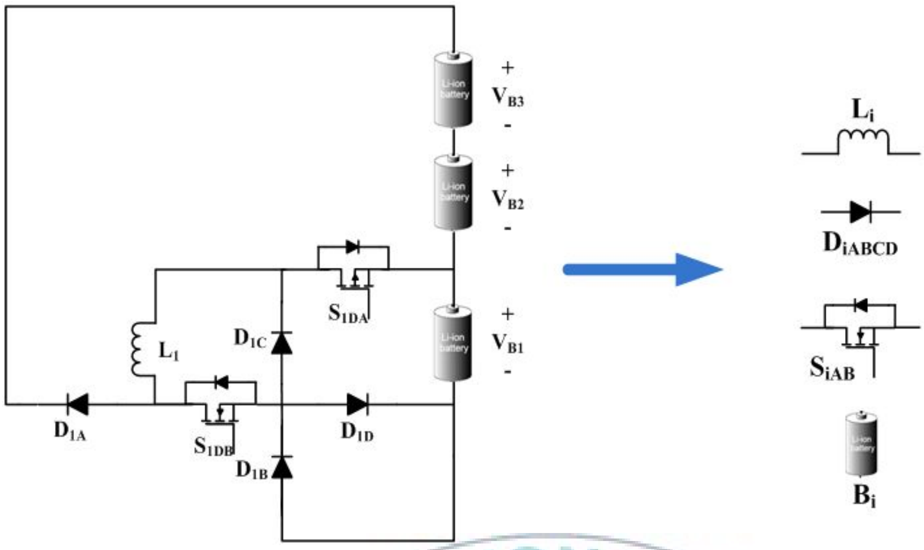


Fig. 3.2 Cell B_1 module in the balance diagram

3.2 Cell Current Analysis

The principle of the proposed work is that the equalization energy from the target battery cell moves to battery pack through the inductors and cell selection switches. It simply makes the equalization current path between the inductors and the battery stacks.

When the battery works in the charging and discharging process, the two different current loops are composed. The two MOSFET switchings are turned on, for higher voltage cells, the voltage on the battery side is higher than that on the inductor side. Hence battery energy will flow out of this cell and go into the corresponding inductor. As far as lower voltage cells, the voltage on the battery side is lower than that on the inductor side. So energy will flow into the cell stack from the inductor which is located in the higher or highest battery capacity module. It can be seen that the energy transfers from higher voltage cells to batteries series connected pack directly and energy is distributed evenly into each battery.

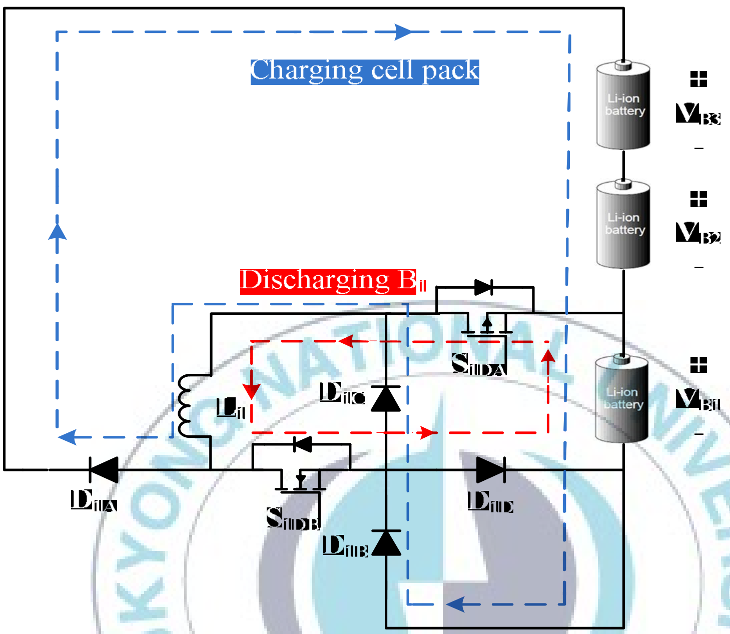


Fig. 3.3 Equivalent circuit with discharging B_1 and charging battery pack

For instance, while the battery B_1 in the discharging condition. Two switchings, S_{1DA} and S_{1DB}, are turned ON, energy flows out of the battery B_1 and then moves into the inductor L_1. The current runs through cell B_1, S_{1DA}, L_1, S_{1DB}, D_{1D}. We can see current direction is expressed with red line in the Fig.3.3.

When the B_1 is charging and two switchings are in OFF state Energy which is stored in the inductor L_1 transmits to the battery string. the current loop is described by blue line in the Fig. 3.3.

This paper studies that there battery cells to be balanced. In accordance with the above analysis, we can easily get the current change of various modules in the balance circuit is shown in Fig. 3.4.

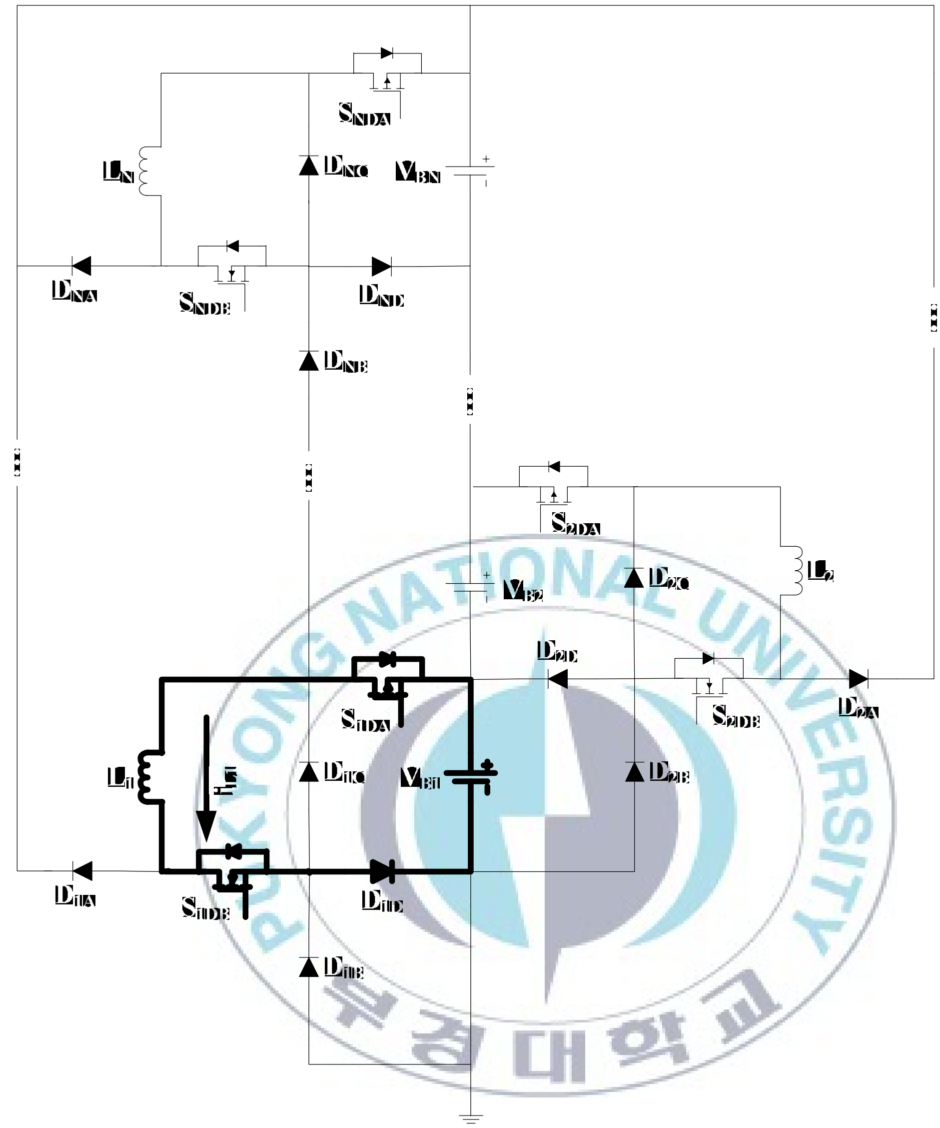


Fig. 3.4 Current paths under cells are charging and discharging (a) Discharging B_1

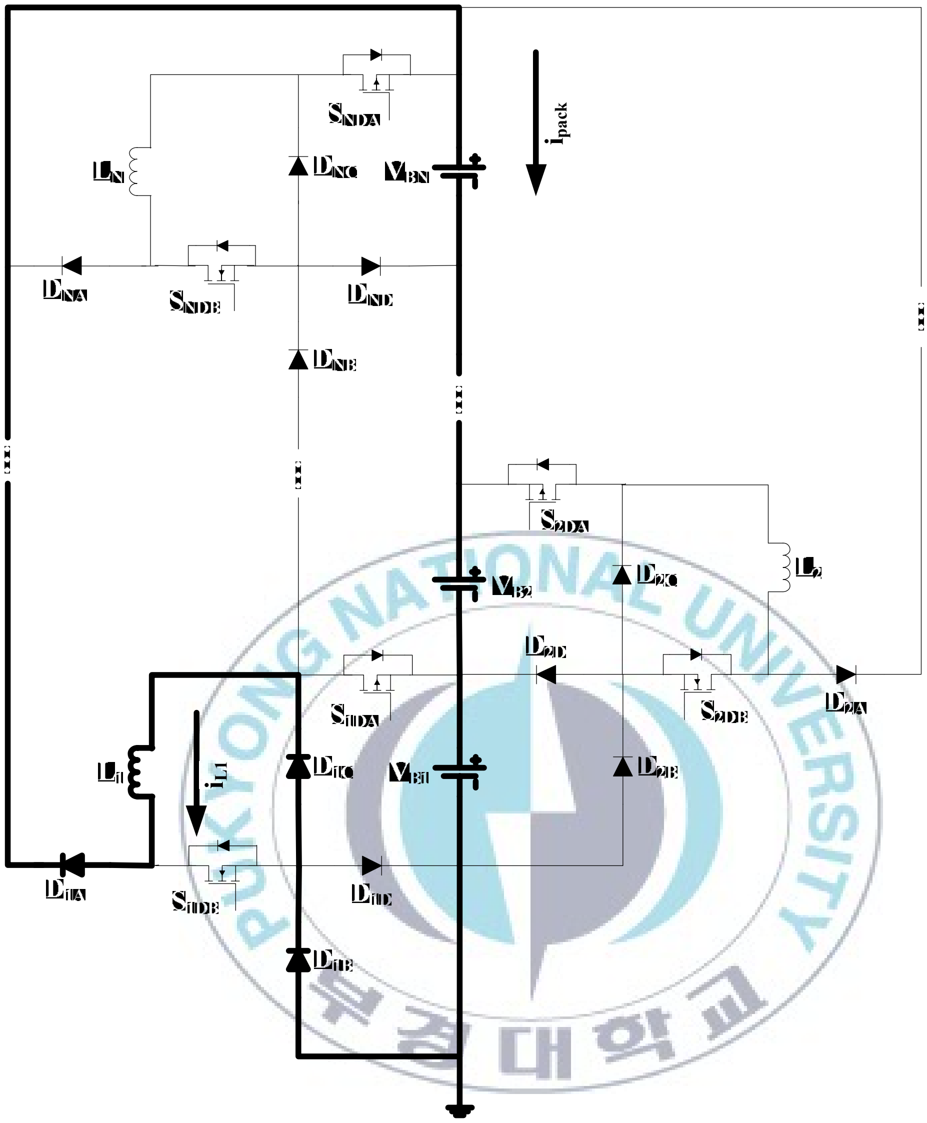


Fig. 3.4 Current paths under cells are charging and discharging operation (b) Energy flows out from L_1 to charge cell stack

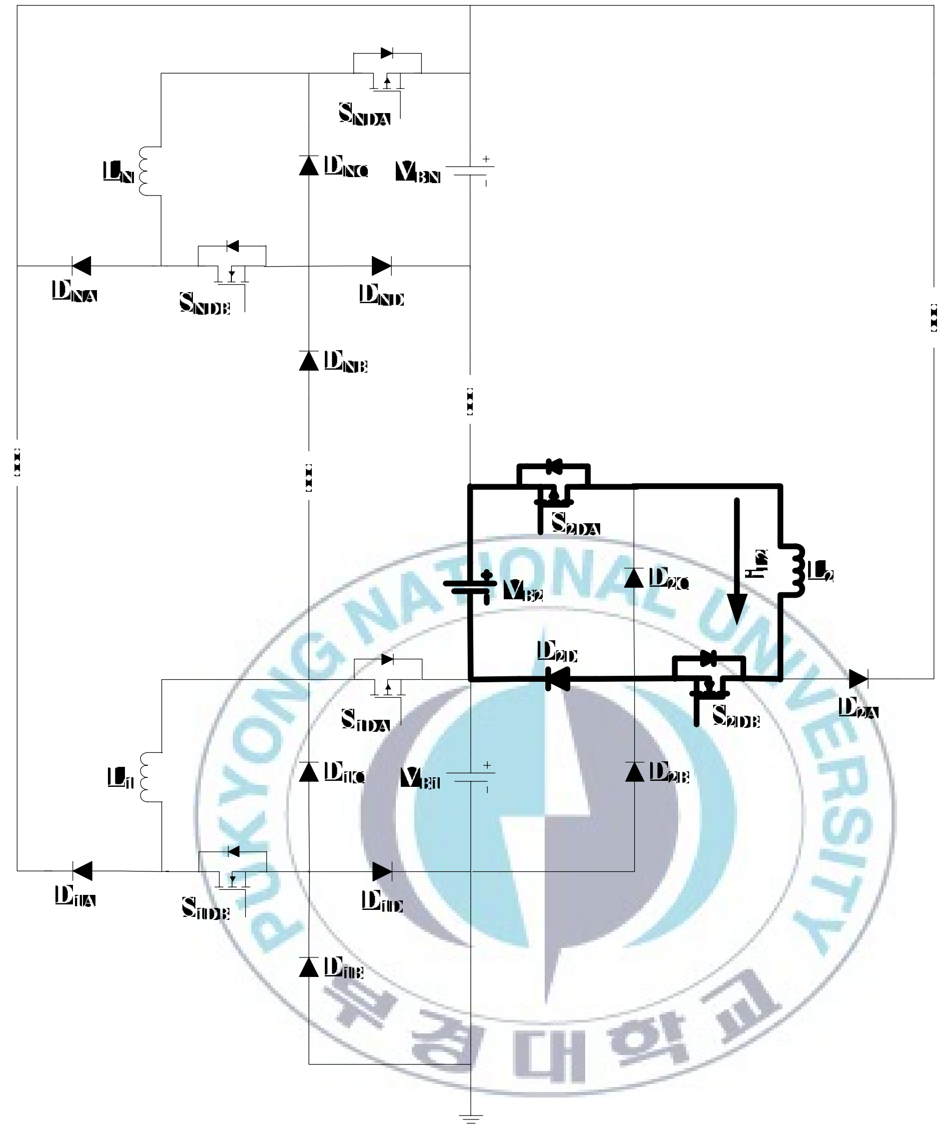


Fig. 3.4 Current paths under cells are charging and discharging operation (c) Discharging B_2

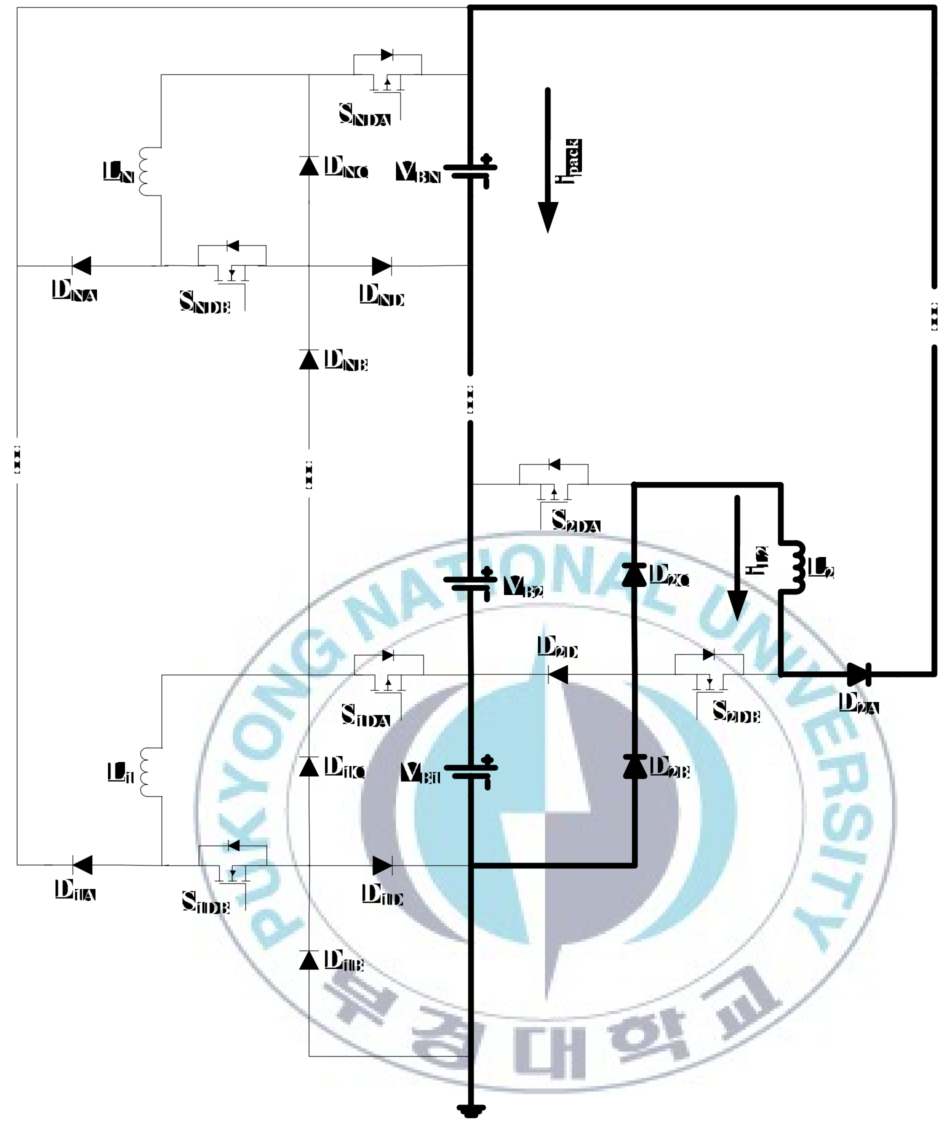


Fig. 3.4 Current paths under cells are charging and discharging operation (d) Energy flows out from L_2 to charge cell stack

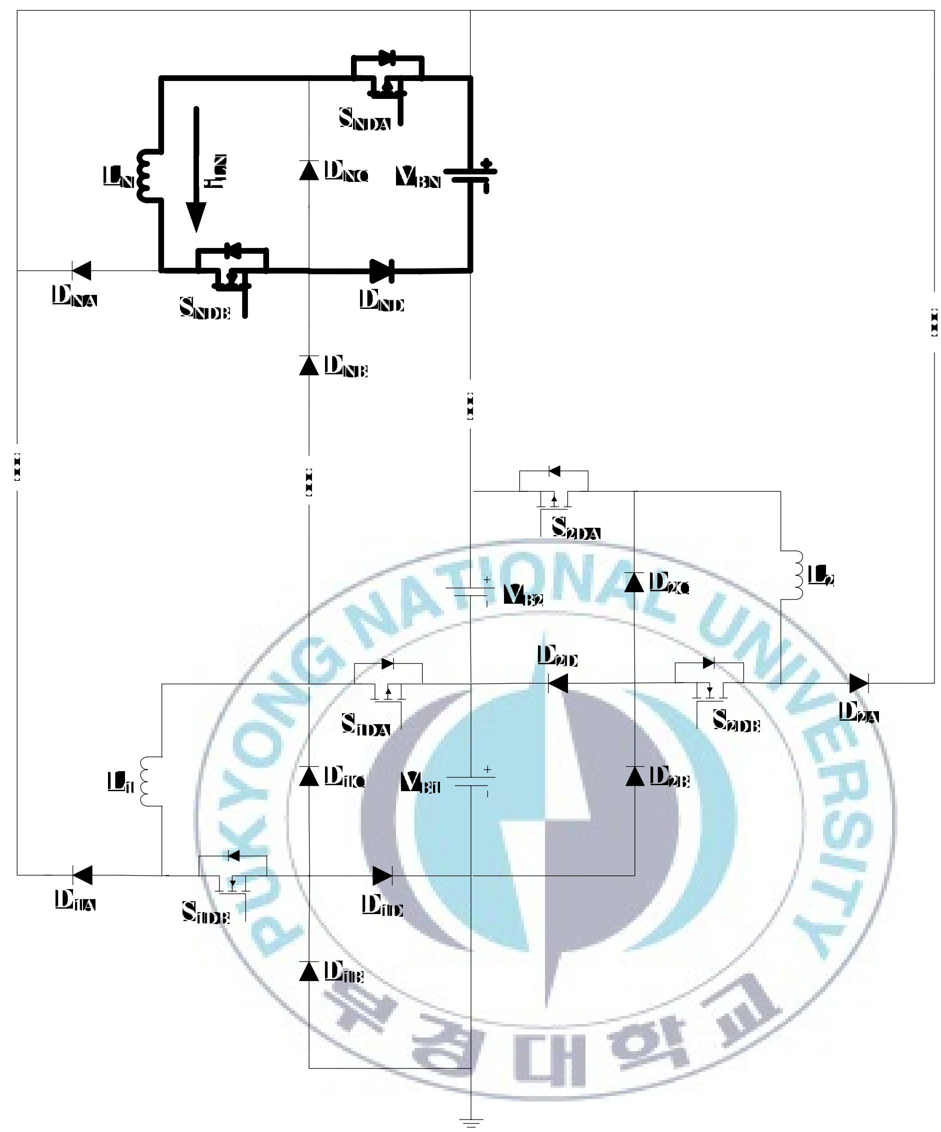


Fig. 3.4 Current paths under cells are charging and discharging operation (e) Discharging B_N

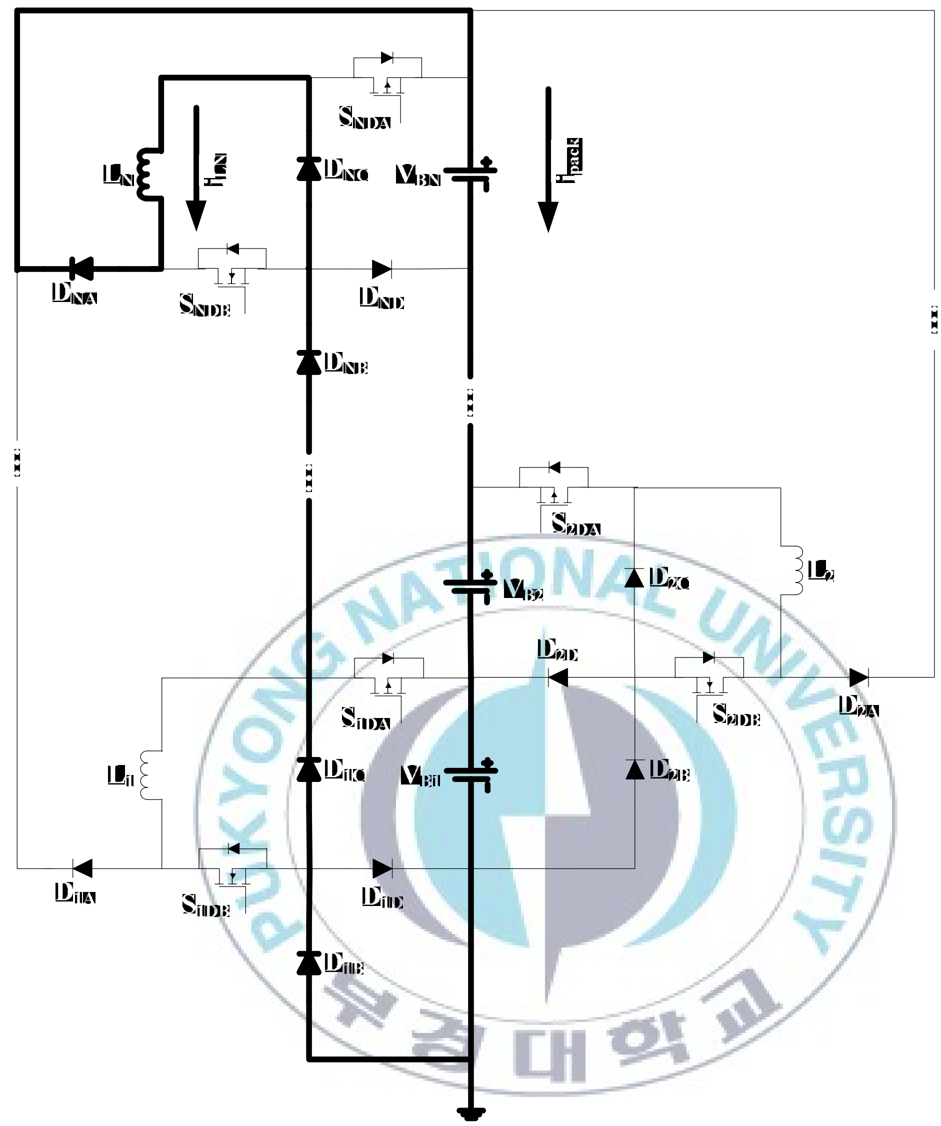


Fig. 3.4 Current paths under cells are charging and discharging operation (f) Energy flows out from L_N to charge cell stack

3.3 Circuit Operation Principle

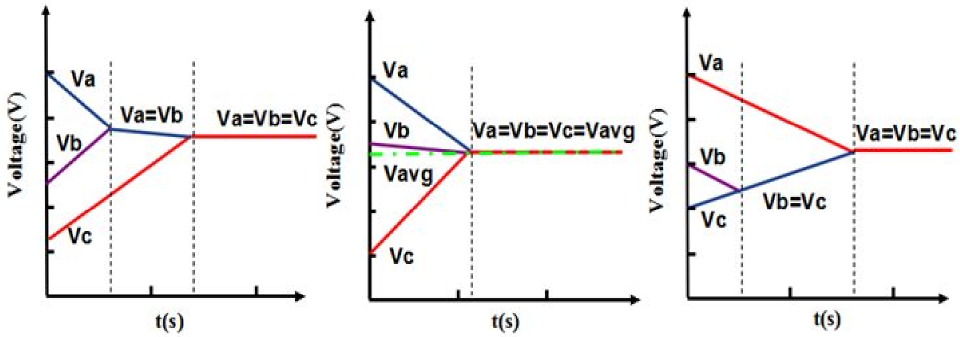
We assume that the balance approach can be categorized into three methods in proposed balance circuit. First, we separately call them the top balancing topology, the bottom balancing topology, and the average balancing topology, as Fig. 3.5 shown.

The top balancing method is that the highest cell and higher cell reach the same battery voltage state first, and then to reach the cell balancing with low battery voltage battery. Bottom balancing method is that the lowest battery and lower battery get the identical voltage and its energy which is from another cell with high battery capacity can be augmented. The last method is average balancing approach, it is a way that to detect each cell voltage and to compare with average cell value, this battery is charging when the current voltage of cell is lower than the average battery voltage, otherwise, the battery is discharging while the present voltage of cell is higher than the average cell voltage.

In this paper, we adopt the average balancing method to analyze the question of balance for the series connected battery stack. Because this method is observed more obviously by referring to the average value.

In the process of charging, when one section of the batteries voltage is more than 4.0 V (this value can be set according to the actual demand), the section of the batteries in the state of PWM switch will work.

Now suppose in rechargeable batteries cell B_1 detected voltage in the process of 4.0V, the cell B_1 balance circuit will start to work at this moment, and it can work in the state of PWM switch S_{1DA} and S_{1DB} are activated. The current on the L_1 began to increase, at the same time, as part of the cell B_1 energy will be transferred to inductor L_1, so energy storage happens naturally.



(a) (b) (c)

Fig. 3.5 (a) Top balancing method (b) Average balancing method (c) Bottom balancing method

During the discharging process, while S_{1DA} and S_{1DB} switches are in off state, because the current on the L_1 cannot be suddenly changed and produces counter electro motive force. Therefore, L_1, D_{1A}, battery string, D_{1B}, and D_{1C} constitute the current loop, the L_1 release energy and the energy transfers to the entire battery stack. This is that the highest voltage cell discharged to balance the whole batteries and the charging current on the high voltage cell is decreased and weakest voltage cell can be increased, repeat the above operation until each battery in the battery cell string meets the same voltage value.

IV. Proposed Battery Equalizer

4.1 Simulation Analysis

In the proposed battery equalizer, the equalization process is achieved by transferring equalization current. The equalization current is extracted from a higher/highest charged battery and the current flows to the battery string.

For the convenience of the analysis of the operation principle, additional assumptions are made as follows:

(1) a series-connected battery string consists of three battery cells;

(2) all diodes are ideal and no voltage drop exists, all switches are ideal;

(3) an identical duty cycle D is applied to $S_{1DA,\ B}$, $S_{2DA,\ B}$, $S_{3DA,\ B}$;

(4) the relationship among the battery cell voltages V_{B1},V_{B2} and V_{B3} and the average voltage V_{Bavg}. The battery B_3 is highest charged cell, B_2 is higher voltage battery and battery B_1 is the weakest charged, their value respectively are 4.0V, 3.8V, 3.4V, and they also can be expressed as $V_{B1}<V_{Bavg}=(V_{B1}+V_{B2}+V_{B3})/3<V_{B2}<V_{B3}$.

4.1.1 Operation Intervals

The circuit steady-state operation consists of three intervals in accordance with the statuses of the switches and the directions of the currents.

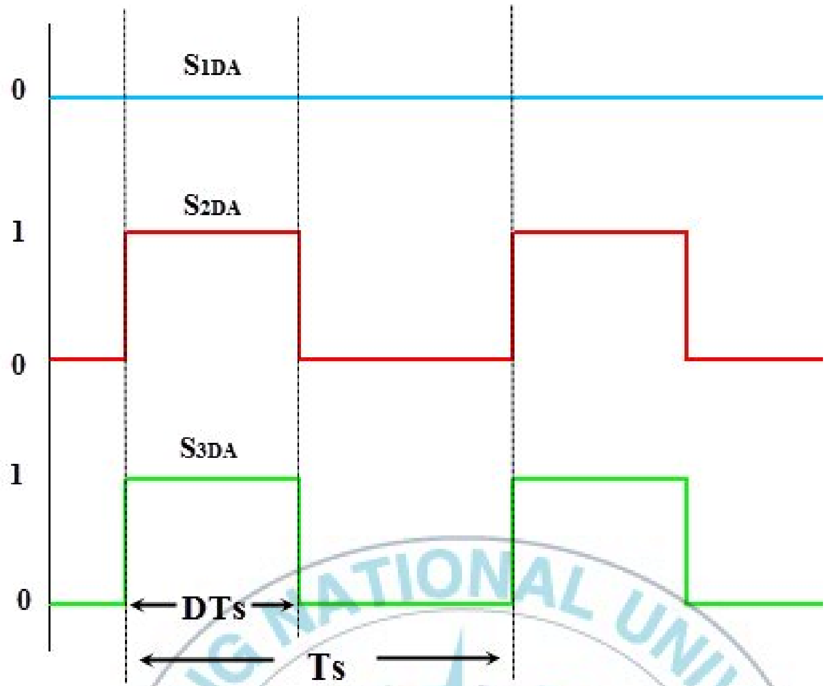


Fig. 4.1 Key waveforms of charge equalization (a) Gate signals

Interval 1 [t_0-t_1]: The charge is extracted from battery B_2 and B_3. Switches $S_{2DA,\ B}$ and $S_{3DA,\ B}$ are turned on at the same time and its duty cycle is DT_S, as Fig.4.1(a) shown, these switches are in the discharging path of battery B_2 and B_3, the current loop is built up and the currents of L_2 and L_3 linearly increase. However, the cell voltage of B_1 is lower than average cell voltage and other two batteries, so the switching in battery module1 are turned off and there is no current flow through L_1. Battery B_1 is waiting for charging. In short, during interval 1, the equalizer circuitry transfers the energy of battery

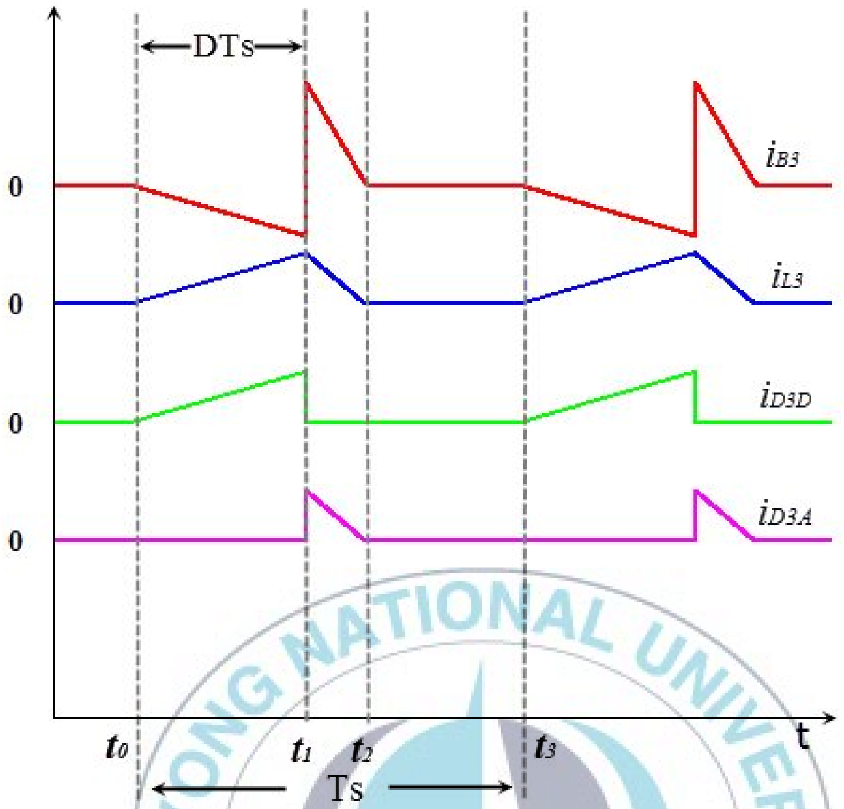


Fig. 4.1 Key waveforms of charge equalization (b) Each current waveform in module 3

$B_{2,\ 3}$ to the inductor $L_{2,\ 3}$. The inductor voltage can be expressed as:

$$v_{L_n} = L\frac{di_{L_n}}{dt} = V_{B_n}(n = 2{,}3) \qquad (2)$$

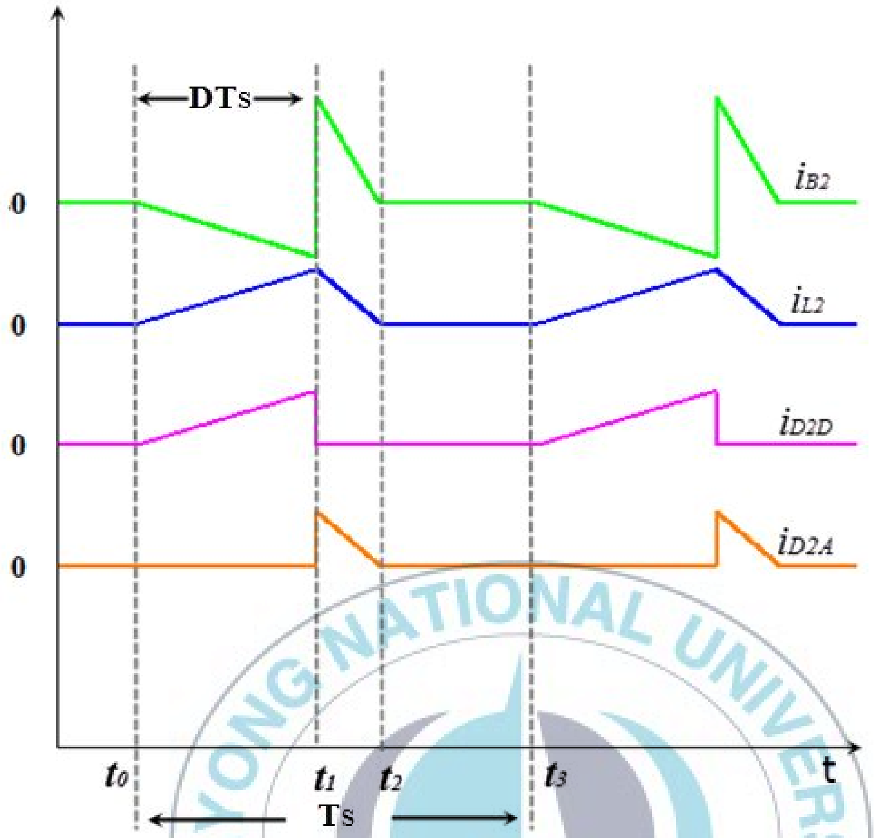


Fig. 4.1 Key waveforms of charge equalization (c) Each current waveform in module 2

And then, equation (2) can be rewritten as

$$\frac{di_{L_n}}{dt} = \frac{\Delta i_{L_n}}{DT_S} = \frac{V_{B_n}}{L_n} (n=2,3) \qquad (3)$$

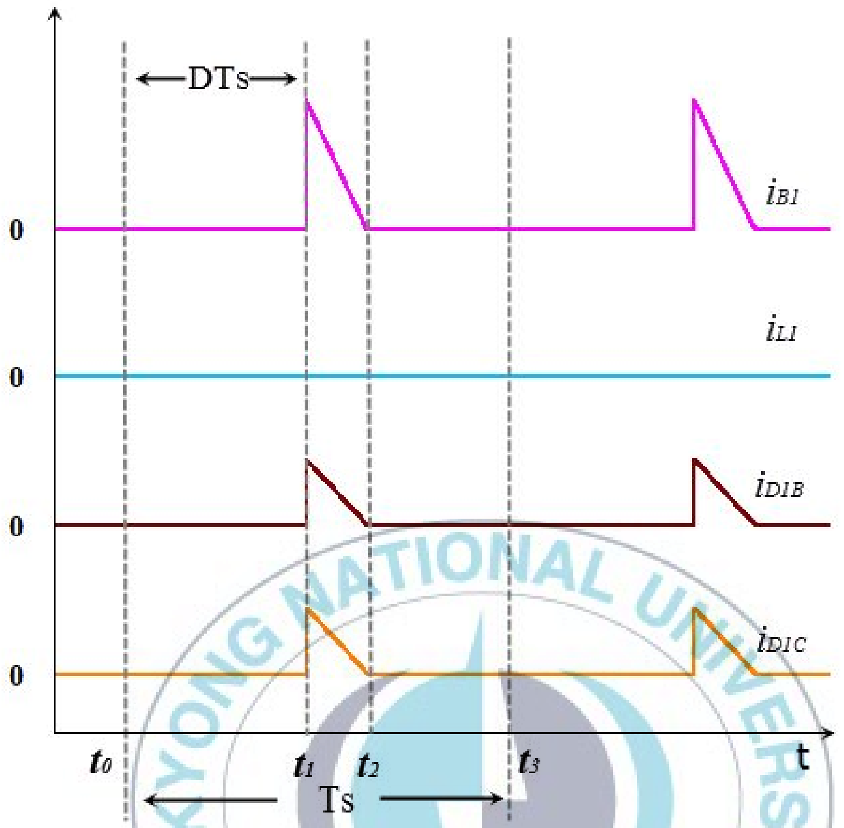


Fig. 4.1 Key waveforms of charge equalization (d) Each current waveform in module 1

Interval 2 [t_1-t_2]: When all switches are turned off simultaneously, interval 2 starts. In this interval, the energy stored in the inductor L will be diverted to the battery pack through D_{2A}, D_{3A}. When the inductor current I_L becomes zero, the current is blocked by the unidirectional switches and the inductor current will not be negative. In summary, during this interval, all the energy are stored in inductor L moves to battery stack. The inductor voltage can be expressed as:

$$v_{L_n} = L\frac{di_{L_n}}{dt} = -V_{stack}\,(n = 2,3) \qquad (4)$$

And then, equation (4) can be rewritten as

$$\frac{di_{L_n}}{dt} = \frac{\Delta i_{L_n}}{(1-D)T_S} = \frac{-V_{stack}}{L_n}\,(n = 2,3) \qquad (5)$$

Interval 3 [t_2-t_3]: The battery balancing can be finished in one cycle, the whole switches are turned off, and wait for the next balancing to occur.

The proposed circuit is to prevent the saturation of the inductor current must be operating in the discontinuous mode. As explained in the description interval for each cell module can be seen that the amount of energy stored in inductor is different. During DT_S and the switchings are turned on, the voltage of inductors follow $V_L(t)=V_B(t)$. While in the $(1-D)T_S$ and the switchings are turned off, the voltage applied to the inductors are follow $V_L(t)=V_{stack}(t)-0$. In this case, the voltage drop of the diodes are neglected under the $(1-D)T_S$, $V_{stack}(t)$ is assumed to be the same value besides.

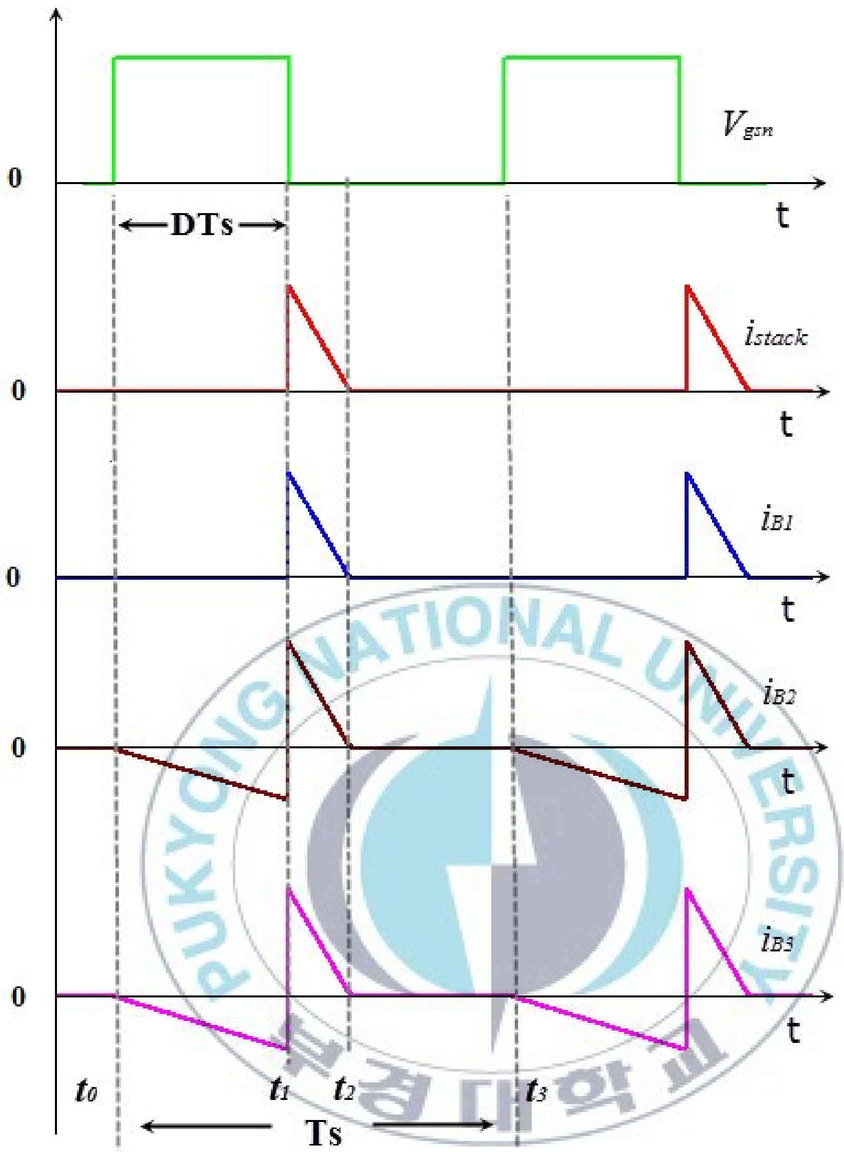


Fig. 4.1 Key waveforms of charge equalization (e) Current waveforms of each cell and battery stack

4.1.2 Waveform analysis

We can see that all current change in a battery charging and discharging process, As Fig. 4.1(b), (c), (d) shown. Fig. 4.1(b) represents the variations during batteries balance of battery module 3, including cell B_3, the inductor L_3, and the diodes D_{3D} and D_{3A}. And cell module 2 has same charging and discharging process as battery module 3, as Fig. 4.1(c) shown, but merely the variable is smaller than cell B_3. By the same token, Fig. 4.1(d) is the change of current in battery module 1. We can know that currents of batteries are same as the battery cell stack when the switches are turned off according to the Fig. 4.1(d).

In charging process, the entire charging current flows through the battery stack constantly. And the proposed equalizer moves the charge of batteries through one inductor L which is in its battery module. When two or more battery cells are high charged at once, those battery cells have to be discharged by turns to avoid overcharging. For this, the discharging current of the equalizer is less than the whole charging current. Eventually, the all batteries are balanced process is shown in Fig 4.2.

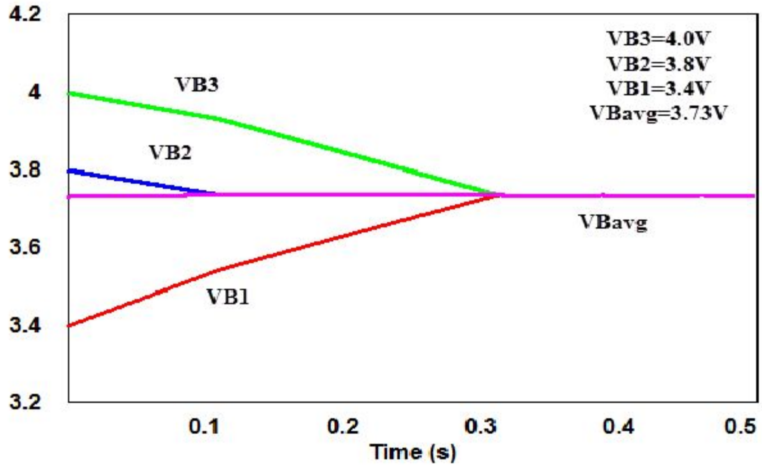


Fig. 4.2 Waveforms of the proposed battery equalizer

The algorithm of the proposed three cells battery equalizer is explained by the flow chart shown in Fig. 4.3. All the operation of the power switches in the battery balancing circuit is controlled by a microcontroller. The microcontroller can judge which cell voltage is higher, and then decide which battery should be executed in discharging process. When the state of battery module is idle and the voltage difference exists among three battery cells, the battery balancing circuit will be initiated. If $V_{BN}>V_{avg}$, then enter cell discharging process. On the contrary, as $V_{BN}<V_{avg}$, this battery cell is waiting to be charged. Each battery voltage and average cell voltage are detected per second and displayed in the LCD. All the above are battery balancing operation in one control cycle.

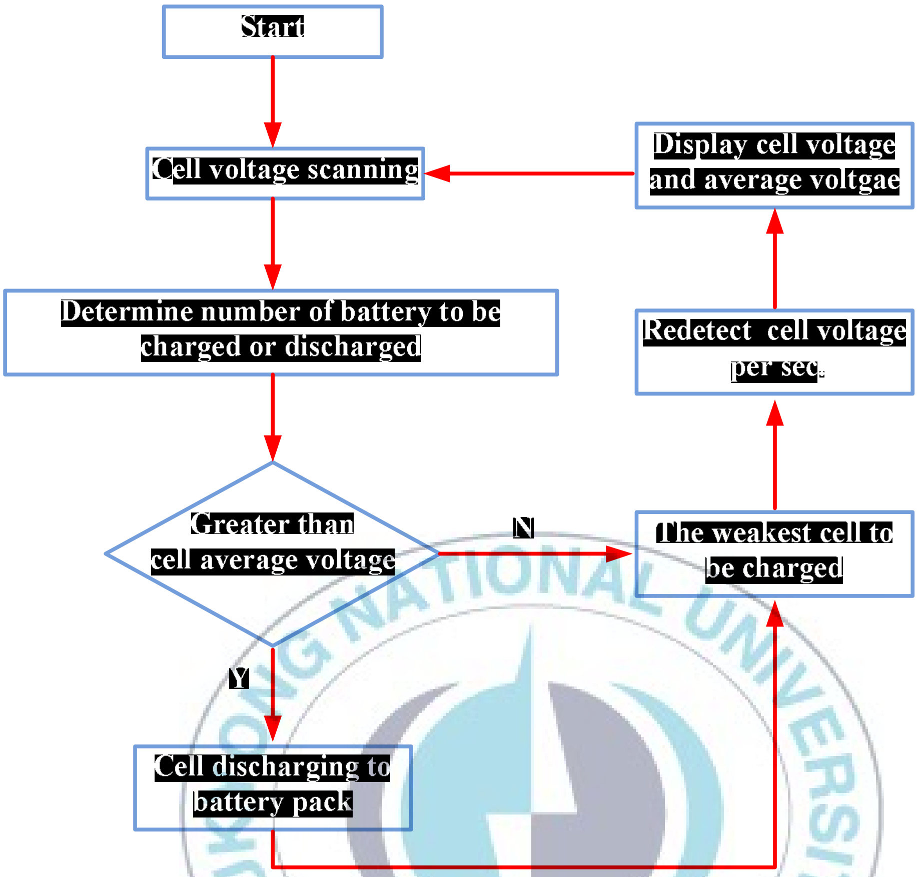


Fig. 4.3 Flow chart of proposed equalizer of one control cycle

4.2 Experimental Results and Discussions

To verify the operation of the proposed battery equalizer, an experiment is performed for a three-cell battery stack. The detailed specifications of the experiment are as Table 2 shown.

Table 2. Balance circuit parameters

SYMBOL	VALUE	COMMENT
$T_s(f_s)$	50μs (20KHz)	PWM SIGNAL PERIOD
D_{max}	0.45	MAXIMUM ON DUTY RATION IN SWITCHING
L_N (N=1,2,3)	30uH	INDUCTANCE
S_{NDA} (N=1,2,3)	IRF7424	P CHANNEL MOSFET
S_{NDB} (N=1,2,3)	IRF7807Z	N CHANNEL MOSFET
D_{NA},D_{NB},D_{NC},D_{ND} (N=1,2,3,)	SS54CF	SCHOTTKY BARRIER RECTIFIERS
V_{B1}	3.40V	INITIAL LI-ION BATTERY VOLATGE
V_{B2}	3.80V	INITIAL LI-ION BATTERY VOLATGE
V_{B3}	4.00V	INITIAL LI-ION BATTERY VOLATGE

Fig. 4.4 shows a photograph of the prototype. A series connected battery string of three cells are used, and for this string, three modularized battery cells are located in the area A. In the area B, 3-terminal positive adjustable regulator to be used to get two input voltages, one is 5V and another is 14V. The pulse width modulation (PWM) signal is generated by timer 555 in section C and to achieve the ideal gate signal which the maximum duty ration is 0.45 in the region D. Finally the module micro-controller is built up in the part E.

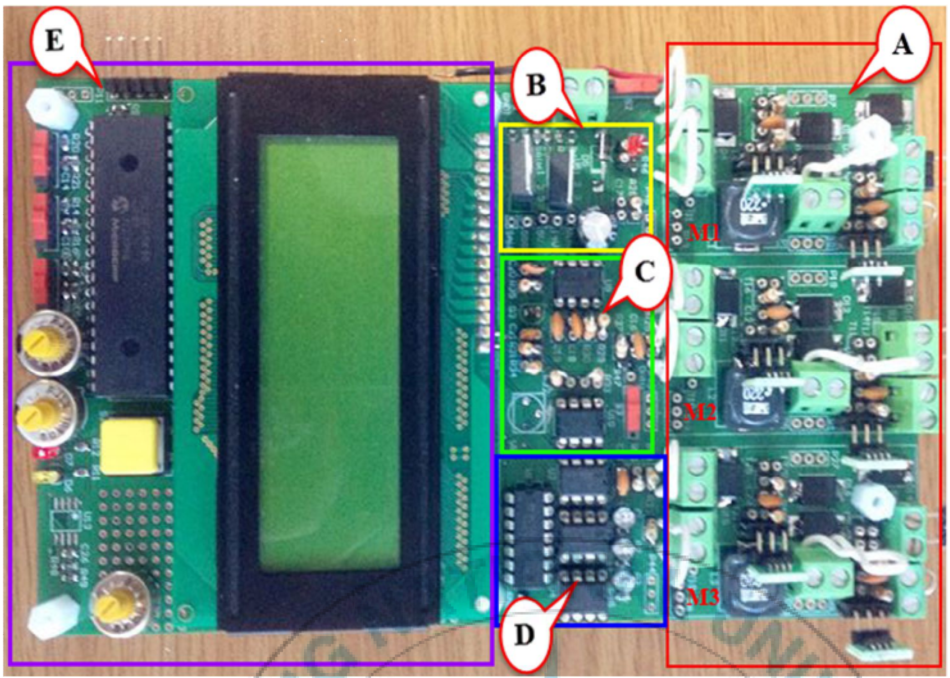


Fig. 4.4 The photograph of an implemented prototype

The switching frequency of the proposed circuit is designated at a same frequency of 20 kHz with a maximum duty-ratio of 0.45. It is a secure way to set the rate ration below 0.5 because the battery cell voltage is extremely low when the circuit breaks down. And in this paper, inductor current is rising during the period of DT_S. Even if all batteries voltage is zero in the current loop, the voltage of the inductor is inversely applied to the batteries while the period of $(1\text{-}D)T_S$, is also the reason why to prevent the minimum inductor reaching saturation.

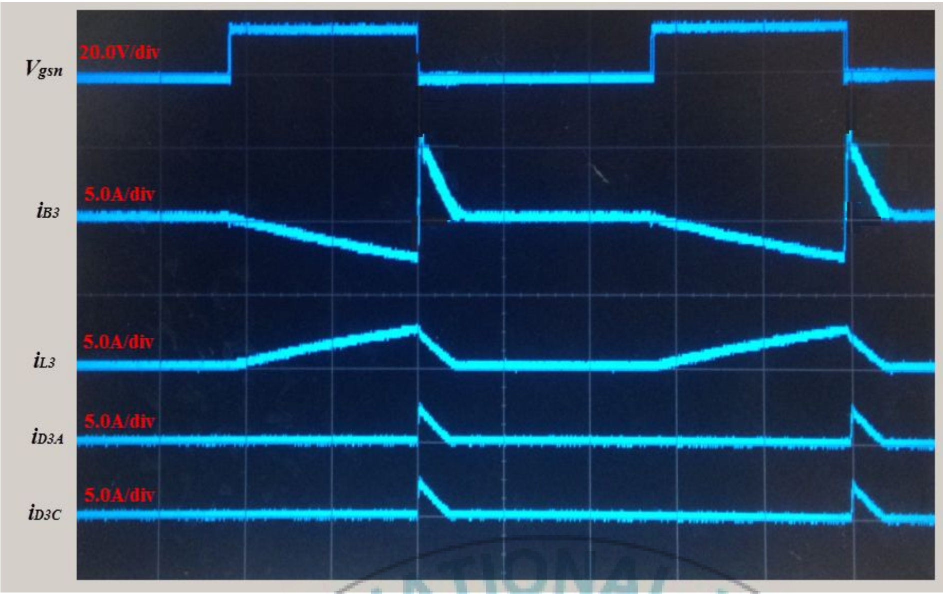


Fig. 4.5 Current curves in the cell B_3 discharged process

Fig. 4.5 shows the balancing current waveforms of higher battery, the inductor and diodes in equalizing process. In this case, first cell B_2 and B_3 discharged before charging the whole battery stack. Due to these two batteries are in same discharging process, so it can be indicated by one figure. As the Fig. 4.5 shown, the peak inductor current and the maximum diodes current are 3A when they are observed in 5A/div, and then the each battery current in the balancing process can be measured in 5A/div and the maximum value is 5A as shown in the Fig. 4.6.

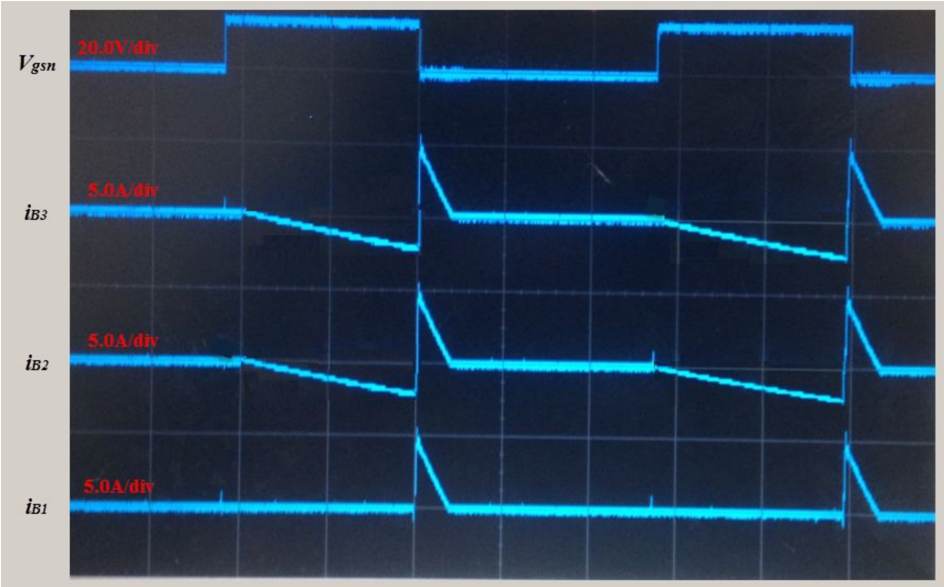


Fig. 4.6 Current curves of each battery in the balancing process

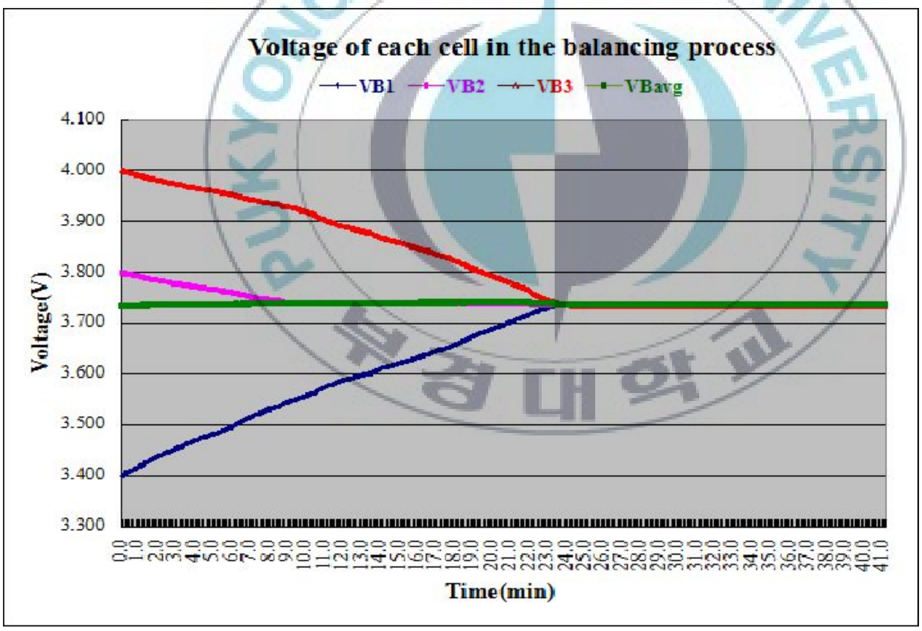


Fig. 4.7 Experimental Result of the Proposed Battery Equalizer

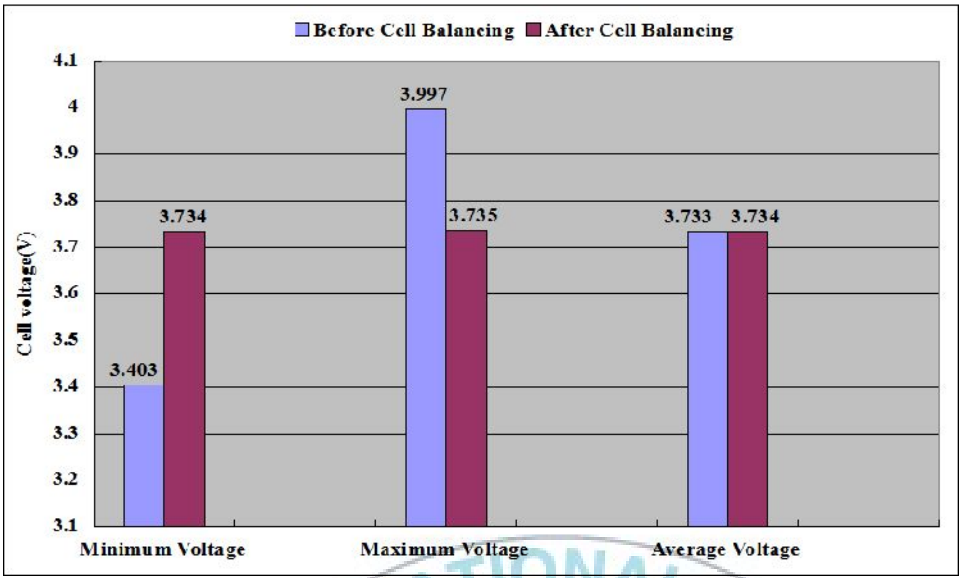


Fig. 4.8 Battery cell state before and after active cell balancing

Fig. 4.7 shows the cell balancing performance of the proposed battery equalizer. The gap of voltage is diminished after cell balancing for 24 minutes. Battery states before and after cell balancing are shown in Fig. 4.8. After active cell balancing, the minimum voltage (V_{B1}) is increased as about 331mV and the voltage reduction of the maximum voltage(V_{B3}) is 262mV. The average voltage is nearly the same with that before cell balancing when the active cell balancing is completed. High performance of active cell balancing is also shown in the experimental results.

Table 3. Comparison between the proposed equalizer and conventional chargers

Topology	Capacitive energy transfer		Inductor/ Transformer base		Converter energy transfer		
	Switched capacitor [26]	Double Tiered [27]	Multi winding [28]	Proposed topology	Multi-stacked Buck-boost [29]	Module Flyback [30]	Cûk [31]
MOSFET	2n	2n	2	2n	1	n+m(m= No. of modules)	2(n-1)
Capacitor	n-1	2n-3	0	0	n+1	0	n-1
Inductor	0	0	2n	n	n+1	2n	2(n-1)
Diode	0	0	n	4n	n	0	0
Transformer	0	0	1	0	1	1	0
Approx. Efficiency	G	G	G	VG	G	S	G
Control Complexity	M	M	C	M	C	C	C
Equalization Speed	L	S	G	G	G	S	G
Implement -ation Simplicity	VG	VG	G	G	G	G	G
Modularity	H	L	L	E	G	G	M
Application	M/H	M/H	M	M/H	M/H	M/H	M/H
Charge/ discharge	B	B	Charge	B	B	B	B
Size	G	G	S	VG	S	S	G
Cost	L	S	S	S	H	H	H

G: Good; VG: Very good; E: Excellent; M: Medium; C: Complex; H: High; L: Low; B: Bidirectional; S: Satisfactory.

Table 3 gives a comparative study of the proposed equalizer with the existing solutions and the last row of Table 3 shows a comparison in terms of cost of the solutions for battery banks. All of these existing solutions provide good performance targeting small number of cells. However, capacitive energy transfer with high number of capacitors, multiple transformer and converter energy transfer topologies require large number of inductors for large battery bank. Although conventional chargers can be configured with fewer switches or passive components, the need for a multi winding transformer is the major drawback in terms of design and modularity. On the other hand, due to the module technology is adopted in this proposed balancing equalizer, the circuit complexity and size can be significantly reduced when compared with conventional equalizers. Furthermore, the extendibility is also considered to be good because of the absence of a multi winding transformer, and the number of series cell connections can be arbitrarily extended by stacking a circuit consisting of only one inductor and diodes.

V. Conclusions

Charge equalization is a major issue in charging series connected batteries. It concerns the efficiency of the charging process and the prolongation of battery lifetime. In this paper, a new battery equalizer is proposed. The operation principle is analyzed and experimental results are given to verify the analysis. Based on the simulations and the experimental results show that the presented method can meet the balanced state more efficiently. This simple but elegant circuit solution exhibits many favorable features such as high efficiency operation and easily control. This topology uses only one inductor for each cell module in the battery pack, and the number of cells in a string could be increased without any apparent limitations. The proposed charge equalizer not only to take full advantage of the inductor and the transformer merits which are good efficiency and fast equalization speed, but also it is according to a battery modularization technique, and by modularizing the battery string into a small number of groups, it can ensure that the battery balancing design is easy and flexible. In addition, there is an excellent implementation and cost savings by using the proposed modularized Lithium-ion battery equalizer.

References

[1] A. Affanni, A. Bellini, G. Franceschini, P. Guglielmi, and C.Tassoni,"Battery Choice and Management for New-Generation Electric Vehicles", IEEE Trans. Ind. Electron., vol. 52, no.5, pp.1343-1349, October 2005.

[2] B. T. Kuhn, G. E. Pitel, and P. T. Krein, "Electrical properties and equalization of lithium-ion cells in automotive applications", in Proc. IEEE Vehicle Power and Propulsion conference 2005, pp. 55-59, September 2005.

[3] C.S. Moo, Y.C. Hsieh, I.S. Tsai, et al. "Dynamic charge equalization for Series connected batteries", IEEE Proc. Electr. Power Application, pp. 501-505, 2003.

[4] Imtiaz, A.M., Khan, F.H., Kamath, H, "A low-cost time shared cell balancing technique for future lithium-ion battery storage system featuring regenerative energy distribution", Applied Power Electronics Conference and Exposition (APEC), 2011 Twenty-Sixth Annual IEEE, pp.792-799, March 2011.

[5] Daowd, M., Vrije Univ. Brussel, Elsene, Belgium, Omar, N., Van Den Bossche, P.,Van Mi erlo, Joeri, "Passive and Active Battery Balancing comparison based on MATLAB Simulation", Vehicle Power and Propulsion Conference (VPPC), 2011 EEE, pp.6-9, September 2011.

[6] Bharath Pattipati1, Krishna Pattipati1, Jon P. Christopherson2, Setu

Madhavi Namburu3, Danil V. Prokhorov3, and Liu Qiao3, “Automotive Battery Management Systems”, AUTOTESTCON, 2008 IEEE, pp.581-586, September 2008.

[7] W.F. Bentley, “Cell balancing considerations for lithium-ion battery systems”, 12th annual Battery Conference on Applications and Advances, pp.223-226, January 1997.

[8] S. Moore and P. Schneider, “A Review of Cell Equalization Methods for Lithium Ion and Lithium Polymer Battery Systems", in Proceedings of the SAE 2001 World Congress, Warrendale, PA, Detriot, MI, 2001.

[9] N. Kutkut, H. Wiegman, D. Divan, and D. Novotny, “Design considerations for charge equalization of an electric vehicle battery system”, IEEE 1995 Applied Power Electronics Conference Proceedings, pp. 96-103, March 1995.

[10] Kong Zhi Guo, Zhu Chun Bo, Lu Ren Gui, and Cheng Shu Kang, “Comparison and Evaluation of Charge Equalization Technique for Series Connected Batteries”, 37th IEEE power Electronics Specialists Conference, Jeju, Korea: pp. 1-6. 2006.

[11] Jian Cao, Nigel Schofield and Ali Emadi, “Battery Balancing Methods: A Comprehensive Review”, Vehicle Power and Propulsion Conference, 2008. VPPC '08. IEEE, pp.3-5, September 2008.

[12] J. Kim, J. Shin, C. Chun, B.H. Cho, “Stable Configuration of a Li-Ion Series Battery Pack Based on a Screening Process for Improved Voltage/SOC Balancing”, IEEE Transactions on Power Electronics 27, pp. 411-424, 2012.

[13] J.-H. Kim, J.-W. Shin, C.-Y. Jeon, B.-H. Cho, “Screening process of

Li-Ion series battery pack for improved voltage/SOC balancing ”in: International Power Electronics Conference (IPEC), pp. 1174-1179, 21-24 June 2010.

[14] M. Uno, K. Tanaka, “Single-switch single-inductor equalization charger using a voltage multiplier for series-connected energy storage modules” Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference on, pp.2985-2989, May 30 2011-June 3 2011.

[15] Javier Gallardo Lozano, Enrique Romero Cadaval, M. Isabel Milanes Montero, Miguel A. Guerrero-Martinez, “Battery equalization active methods”, Journal of Power Sources, Volume 246, pp. 934-949, 15th January 2014.

[16] Xiaopeng Chen, Weixiang Shen, Thanh Tu Vo, Zhenwei Cao, “An over view of lithium-ion batteries for electric vehicles”, IPEC, 2012 Conference on Power & Energy, pp.230-235, 12-14 December 2012.

[17] M. Barak, T. Dickinson, U. Falk, J.L. Sudworth, H.R. Thirsk, F.L.Tye, electrochemical Power Sources, “Primary & Secondary Batteries”, IEEE energy Series 1, A. Wheaton &Co, Exeter, 1980.

[18] Powers, R.A.; “Batteries for Low Power Electronics”, Proceedings of the IEEE, Volume 83,Issue 4, pp. 687-693, April 1995.

[19] M.J. Riezenman, “The Search for Better Batteries”, IEEE Spectrum, pp. 51-56, May 1995.

[20] D. Linden, “Handbook of Batteries”, Second Edition, McGraw Hill, New York, 1995.

[21] Languang Lu, Xuebing Han, Jianqiu Li, Jianfeng Hua, Minggao Ouyang, “A review on The key issues for lithium-ion battery

management in electric vehicles", Journal of Power Sources, Volume 226, pp. 272-288, 15 March 2013.

[22] Kong Zhi guo, Zhu Chu bo, Lu Ren gui, Cheng Shu kang, "Comparison and Evaluation Of Charge Equalization Technique for Series Connected Batteries", Power Electronics Specialists Conference, PESC '06. 37th IEEE, 2006.

[23] Michael D. Mulligan, Bill Broach, and Thomas H. Lee, "A Constant Frequency Method For Improving Light-Load Efficiency in Synchronous Buck Converters", Power Electronics Letters, IEEE Volume 3, Issue 1, pp. 24 - 29, March 2005.

[24] Moon-Young Kim, Chol-Ho Kim, Jun-Ho Kim and Gun-Woo Moon, "A modularized BMS with an active cell balancing circuit for lithium-ion batteries in V2G system", Vehicle Power and Propulsion Conference (VPPC), 2012 IEEE pp. 401-406, 9-12 October 2012.

[25] Thanh Hai Phung,Crebier, J.-C.,Chureau, A.,Collet, A., "Optimized structure for next-to-next balancing of series-connected lithium-ion cells", Applied Power Electronics Conference and Exposition (APEC), 2011 Twenty-Sixth Annual IEEE, pp.1374-1381, 6-11 March 2011.

[26] C. Pascual and P. T. Krein, "Switched capacitor system for automatic series battery equalization", in Proc. IEEE Applied Power Electronics Conference and Exposition, APEC 97 conference proceedings, pp. 848-854, 1997.

[27] A. C. Baughman and M. Ferdowsi, "Double-tiered switched-capacitor battery charge equalization technique", IEEE Trans. Ind. Electron., vol. 55, no. 7, pp. 2277-2285, June 2008.

[28] Dorin V. Cadar, Dorin M. Petreus and Toma M. Patarau, “An Energy Converter Method for Battery Cell Balancing”, IEEE 33rd International Spring Seminar on Electronics Technology (ISSE), pp. 290-293, 2010.

[29] M. Uno and K. Tanaka, “Single switch cell voltage equalizer using multi-stacked buck boost converters operating in discontinuous conduction mode for series connected energy storage cells”, IEEE Transaction on vehicular technology, Volume 60, no. 8, pp. 3635-3645, October 2011.

[30] H. S. Park, C. E. Kim, C. H. Kim, G. W. Moon, and J. H. Lee, “A modularized charge equalizer for an HEV lithium-ion battery string,” IEEE Trans. Ind. Electron., vol.56, no. 5, pp. 1464-1476, May 2009.

[31] Lee Yuang-Shung, D. Chun-Yi, Chen Guo-Tian, and Yang Shen-Ching, “Battery Equalization Using Bi-directional Cuk Converters in DCVM Operation”, IEEE, 36th Power Electronics Specialists Conference, PESC '05, pp. 765-771, 2005.