LI-ION BATTERY CHARGE BALANCING CIRCUIT FOR APPLICATION IN ELECTRIC VEHICLES

BY

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A thesis submitted in fulfilment of the requirement for the degree of Master of Science (Electrical Engineering)

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ABSTRACT

Electric vehicles (EVs) are becoming popular and considered as future transportation with the apparent capability of zero fuel consumption and pollution. In case of the hybrid electric vehicles and energized battery vehicles are more efficiently used in private and public transportation systems. In the EVs system, an energy storage device is main concern due to charge and discharge issue. This device faces some problems which are electrochemical cell voltage imbalance, state of charge imbalance and state of discharge imbalance. These problems occur due to cell chemical digression, internal resistance and temperature effects which reduce the lifecycle and performance of the cell. Also storage devices are challenged a formidable to immediately deliver the unpredictable driving power required by the electric vehicle. Therefore, the effective voltage balancing technique is highly necessary to balance the voltage differences between cell to cell in the battery pack. Balancing circuits are taken for a long time, which create a voltage gap. To overcome this issue, a design of single resonant converter-based active charge balancing circuit is used to reduce the balancing time and voltage gap. This balancing circuit performs on charging, discharging and inoperative mode. A single series LC tank is connected with switching components and battery cells. The balancing speed has been improved by allowing energy transfer between any two cells in the battery string, and power consumption for balancing is reduced by operating all switches in the circuit at a zero-current switching condition. In general, high spark current is introduced in the inductor that can damage switching devices. Experimental results represented that the balancing circuit provides the balancing current to the cell, which reduces the voltage differences between any cells to cell. The results exposed two 4400mAh Li-ion batteries voltage balancing process. The initial voltage gap between two batteries is 246 mV and the voltage deviation was reduced of 0 mV whereas the voltage balancing process terminated. In addition, the total time duration of the tested voltage equalization process is 76 minutes. This circuit proves an effective and automated system to balance the battery charge that improves the safety and life cycle of the battery. Therefore, this balancing circuit is applicable to equalize the unbalanced voltage of the batteries in electric vehicles and energy storage systems.

خلاصة البحث

أصبحت المركبات الكهربائية (EVs) واسعة الانتشار وتعدّ وسيلة نقل في المستقبل وذلك لقدرتها الواضحة على عدم استهلاك الوقود وبالتالي عدم مساهمتها في التلوث. في حالة المركبات الكهربائية الهجينة والمركبات المزودة بطاقة البطارية، فإنها تعمل بكفاءة أكبر في أنظمة النقل الخاصة والعامة. وفي نظام EVs، فإنّ جهاز تخزين الطاقة هو موضع الإهتمام الرئيسي بسبب مشكلة الشحن والتفريغ. ويواجه هذا الجهاز بعض المشاكل ومنها حالة عدم توازن الخلايا الكهروكيميائية ، وحالة عدم توازن الشحن وكذلك حالة عدم توازن التفريغ. تحدث هذه المشكلات بسبب انحراف الخلية الكيميائية، والمقاومة الداخلية، وتأثير درجة الحرارة التي تقلل من دورة حياة وأداء الخلية. كما تواجه أجهزة التخزين تحدّياً كبيراً من حيث التوصيل الفوري للقوة الدافعة غير المتوقعة التي تتطلبها المركبة الكهربائية. لذلك، فإن تقنية الموازنة الفعالة للجهد ضرورية للغاية لتحقيق التوازن بين فرق الجهد مابين خلية وأخرى داخل حزمة البطارية. يتمّ موازنة الدارات خلال فترة طويلة، مما يُحدث فجوة الجهد. وللتغلب على هذه المشكلة ، يتم استخدام تصميم دائرة توازن الشحنة النشطة القائمة على محول الرنين المفرد single resonant converter-based active charge balancing circuit لتقليل وقت التوازن وفجوة الجهد. وتعمل دائرة التوازن على الشحن والتفريغ ووضع التوقف. تمّ توصيل خزان LC من سلسلة واحدة بمكونات التوصيل وخلايا البطارية. وتم تحسين سرعة التوازن من خلال السماح بنقل الطاقة بين أي خليتين في سلسلة البطارية، وتّم كذلك تقليل استهلاك الطاقة لتحقيق التوازن من خلال تشغيل جميع المفاتيح في الدائرة في حالة تحويل التيار الصفري zero-current switching condition. وبشكل عام، يتم إضافة تيار عالِ الوميض في المحرِّض والذي يمكنه أن يتلف أجهزة التحويل. وقد أظهرت النتائج التجريبية أن دائرة التوازن توفر تياراً لموازنة الخلية، مما يقلل من اختلاف الجهد بين خلية وأخرى. كشفت النتائج عن عملية توزان فرق الجهد لبطاريتيّ أيون الليثيوم 4400 ميللي أمبير. وتبلغ فجوة الجهد الأولي بين البطاريتين 246 ميللي فولت وتم انخفاض انحراف الجهد إلى قيمة صفر ميللي فولت في حين انتهت عملية توازن الجهد. بالإضافة إلى ذلك، فإن المدة الزمنية الإجمالية لعملية معايرة الجهد المختبرة هي 76 دقيقة. تثبت هذه الدائرة وجود نظام فعال وآليّ لتحقيق توازن شحن البطارية والذي يحسّن من الأمان وكذلك دورة حياة البطارية. ولذلك، فإنّ دائرة التوازن هذه قابلة للتطبيق لتعادل الجهد غير المتوازن للبطاريات في المركبات الكهربائية وأنظمة تخزين الطاقة.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Electrical Engineering).

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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LIST OF ABBREVIATIONS

BCB	Battery Charge Balancing
BMS	Battery Management System
BVB	Battery Voltage Balancing
CBC	Charge Balancing Circuit
DOD	Depth-of-Discharge
ESD	Energy Storage Device
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engines
Li-ion	Lithium Ion
MS	MOSFET Switches
PHEV	Plug In Hybrid Electric Vehicle
PWM	Pulse Width Modulation
RUL	Remaining Useful Life
SC	Super Capacitor
SOC	State-of-Charge
SOD	State-of-Discharge
SOH	State-of-Health
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

In the field of road transportation, the number of vehicles has increased due to the progression of manufacturing techniques and living standards since the World War II. The majority of the vehicles are driven by the Internal Combustion Engines (ICEs). In ICE, fossil-fuel energy converts into the mechanical energy and heat while emitting the greenhouse gases and other environmentally-damaging materials.

In order to address the global warming, environmental protection and oil-depleting issues a suitable sustainable transportation alternative to the ICE vehicles is required. As alternatives to ICE vehicles, Plug-in Hybrid Electric Vehicles (PHEVs), Hybrid Electric Vehicle (HEVs) and Electric Vehicles (EV) are being brought forth.

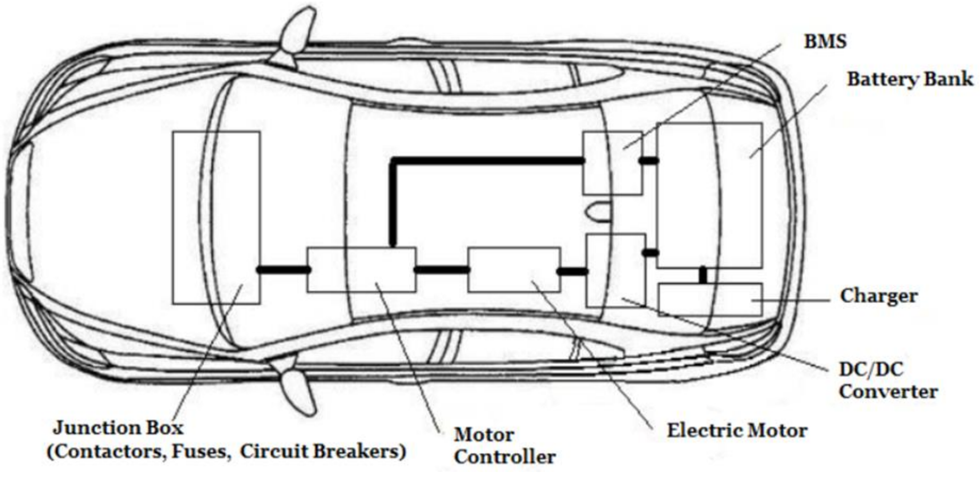

Figure 1.1 Schematic diagram of EV (T. Zhou, 2014)

The EV needs storage electric energy to function. Electric energy storage device is made from batteries or supercapacitors. In a battery pack, all cells or supercapacitors are connected in series or parallel for achieving the required voltage or capacity to drive the electric motor. Different types of cells are used in a battery pack like as Lead acid battery cells, Nickel-Metal Hydride battery cells, Lithium-ion battery cells. The terminal voltage of cells are varied from cell to cell such as 2-3.6 V for lead acid battery cell, 2-3.65V for nickel-metal hydride battery cell and 2.7-4.2 V for lithium-ion battery cell. For the required voltage, a battery pack consists of battery modules and each battery module consists of 50-104 cells. Based on the power demand, the type of battery cells varies such as Mitsubishi electric car of 16 kWh, Honda electric vehicle of 20 kWh, ford hybrid car of 23 kWh and Nissan electric vehicle of 33 kWh (Battery University, 2017). The spark EV, Li-Ion battery cells (336 in numbers) make up the battery pack that is used in General Motors. There cells are connected in parallel (each cell ~3.3 V) and make a battery module. For creating a battery pack, 112 battery modules are connected in series and nominal voltage of the battery pack is 368.6 V DC. When fully charged, it's up to ~ 425 V DC. Nowadays, EV and HEV are under production and development by several manufacturers to improve the fuel economy to meet local issues as well as national and global challenges. Parameters such as energy saving, size, efficiency and cost need to be taken into consideration to improve the energy storage system in EV. The life cycle, cost and performance of EV and HEV depend on battery.

Battery is a device that chemically stores the energy and delivers electrical energy. There are two types of batteries:

- Primary batteries
- Secondary batteries

Primary batteries are those which deliver energy only for once when discharged. Secondary batteries deliver the storage energy cycle wise (charge and discharge) until the end of lifetime. Usually secondary batteries are used in EV. In secondary battery, electric energy to chemical energy (charging time) conversion and chemical energy to electric energy (discharging time) conversion occur via electrons donating (oxidation) and electrons accepting (reduction). These reaction is called redox reaction that occurs at the positive and negative electrode (Berg, 2015 & Yuan *et al.*, 2011). The electrochemical energy storage element that is contained inside a battery is called cell. In a battery, one or more cells are accumulated together in series or parallel to achieve a desired voltage or current. An electrochemical secondary cell fundamental design is shown in Figure 1.2 (Berg, 2015) that generally contains the following elements:

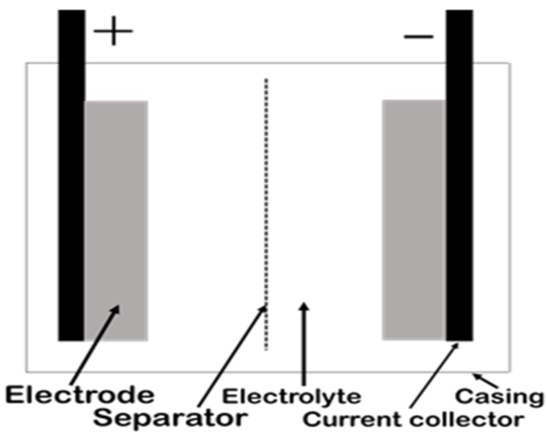

Figure 1.2 Fundamental design of electrochemical secondary battery cell (Berg, 2015)

Anode (Negative Electrode):

Oxidation occurs at this electrode. In the reaction, electrode releases electrons which flow to the cathode. Battery performance depends on the material of the anode selected based upon its high specific capacity, efficiency, stability, conductivity, cost, and ease of fabrication (Berg, 2015 & Yuan *et al.*, 2011).

Cathode (Positive Electrode):

Reduction occurs at this electrode. The cathode accepts electrons from the anode. Based on voltage and chemical stability, suitable cathode material is selected for a battery cell (Berg, 2015 & Yuan *et al.*, 2011).

Electrolyte:

When the electrochemical reaction occurs in a battery cell, electrolyte works as a medium for transferring the ions, charge that flow between anode and cathode. The electrolyte material can be solid, gel or liquid, such as water or solvent/dissolved salt. The electrolyte material is selected based on its non-reactivity with electrode material, high conductivity, stability at various temperatures, cost and safety (Berg, 2015 & Yuan *et al.*, 2011).

A cell voltage is defined as the voltage difference between the anode and cathode. Highest energy capacity and cell voltage is dependent on the combination of cathode and anode material. Practically when a cell is designed, separators are used to provide a mechanical isolation between the anode and cathode.

Cell Operation

During the charging process, the cathode undergoes reduction, accepts electrons, which travel to the anode which loses the electrons and undergoes oxidation. During the discharging process reverse cycle occurs. The free energy decreases on the system when a reaction occurs and this free energy is transformed into electrical energy. Based on active material that is contained in the cell, the standard potential of the cell is determined. It is calculated by the summation of cathodic and anodic potentials. The charge and discharge procedures are shown in Figure 1.3.

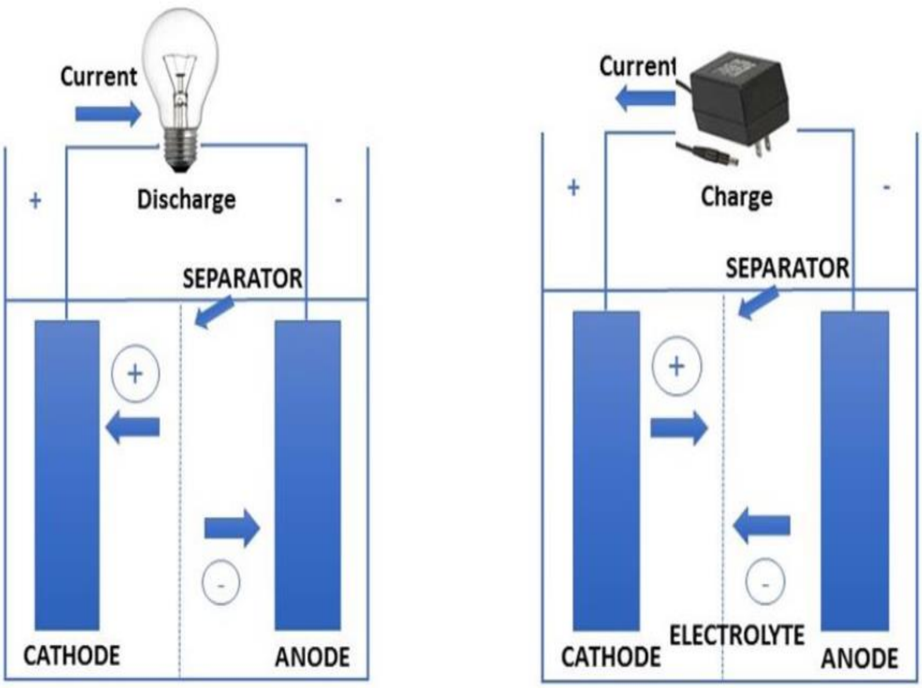

Figure 1.3 Charging and discharging procedure inside an electrochemical cell (Shamsi, 2016)

Lithium-Ion Battery Operation

In Li-ion battery cell, the positive electrode is typical lithium metal oxide and lithium graphite is used to be negative electrode. In charging state, Li-ions are detached from the lithium layered oxide composite of the anode and interpolated into the lithium graphite layers. The procedure is reversed on discharge. Li-ion battery cell required an external current driving circuit for charge balancing at each electrode (Figure 1.5, Dunn *et al.*, 2011) and Li+ transfer from positive electrode to negative electrode by Electrolyte.

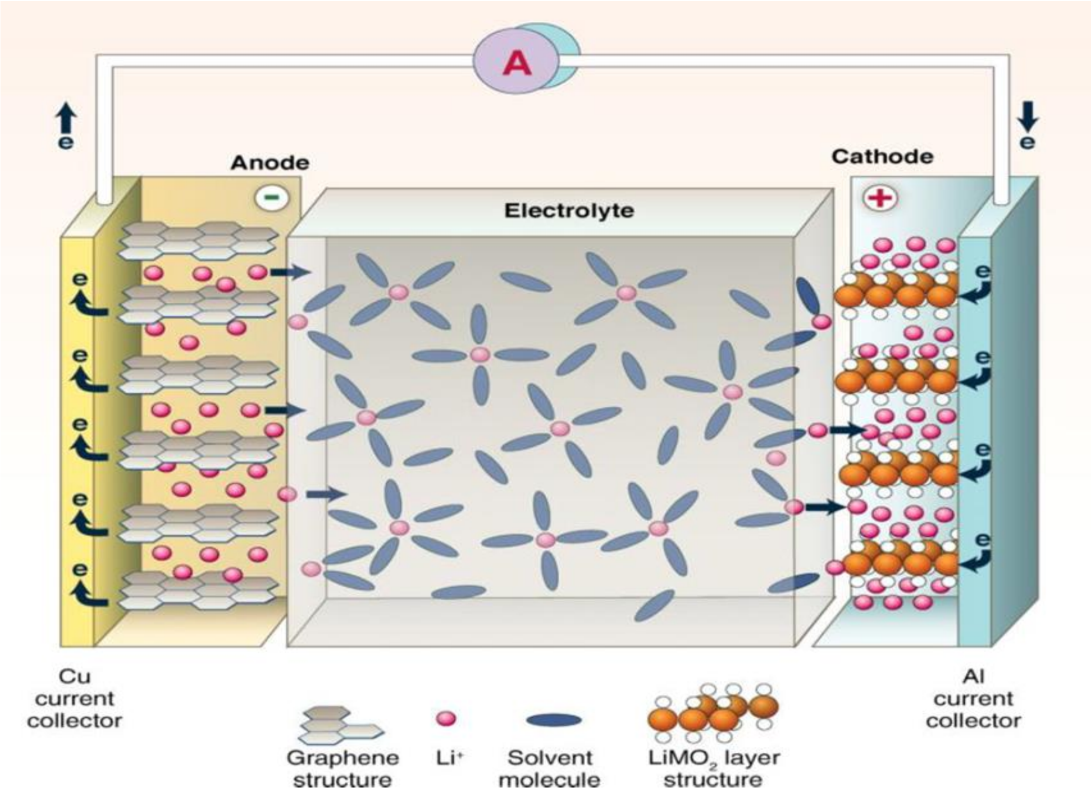

Figure 1.4 Charging process inside a Li-Ion cell (Dunn, 2011)

Lithium-Ion Battery Charge and Discharge Characteristics

Li-Ion battery cells voltage charging and discharging profiles are displayed in Figure 1.6. Li-Ion cells are charged by continuous current- constant voltage logic. In the beginning, the terminal voltage of the cell increases to maximum cell voltage and provides the charging current. The current starts declining as the cell voltage touches the maximum terminal value and the supply is cut off when the cell current drops down to a cut-off value that is specified by the manufacturer. From the figure, Li-ion cell voltage discharge carve offers a flat voltage profile. Initially cell voltage is dropped due to internal cell resistance. The cell is allowed to discharge only when the voltage through the cell becomes equal to the cut-off voltage, which is specified by the manufacturer.

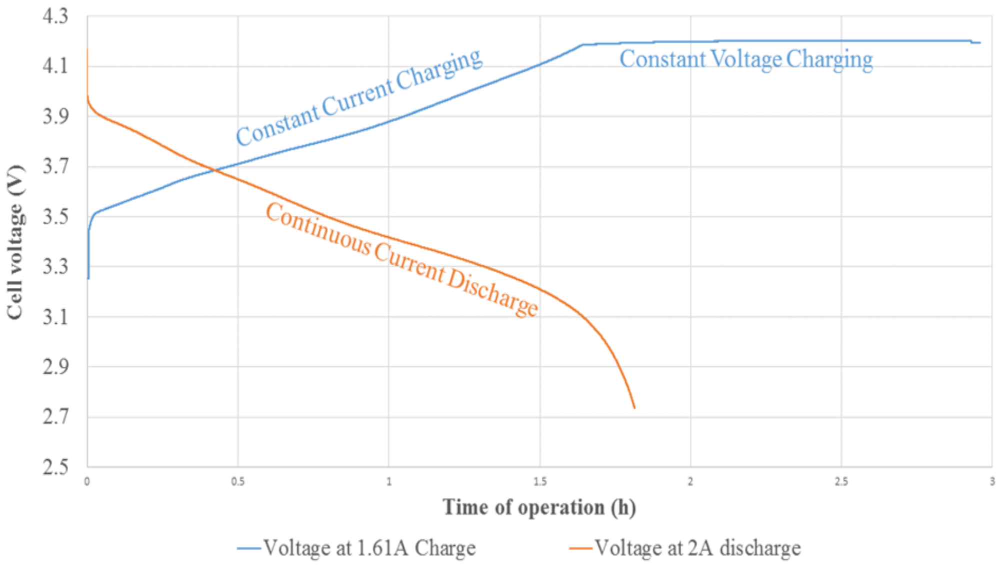

Figure 1.5 Li-Ion battery cells voltage charging and discharging profiles (Shamsi, 2016)

C_Rate

C_rate is determined based on the battery capacity. For instance, a 1C discharge of a 10 Ah battery represents 10A and will discharge the battery in an hour.

$$C\_rate = \frac{I}{Q_{max}}$$

Capacity Measurement

Capacity of the Li-ion cell is measured by the amount of the active element on the electrodes. Moreover, the capacity of a li-ion battery is equivalent to the C rate and declines by a limited percent for higher C rates. Capacity is calculated by the C-rate of the battery and the number of hours. For example, a battery delivers the C Amperes current with an hour. Battery capacity decreases by the internal resistance at higher C-rate. Minimum voltage and current range are specified by manufacturers so that battery can be extracted (Andrea, 2010).

$$Battery\ Capacity = C - rate\ (A) * Time\ (h)$$

State of Charge (SOC) and Depth of Discharge (DOD)

Battery or cell charge that is contained in battery or cell at a certain time is expressed by the term of SOC. SOC is expressed by the percentage, for example, a battery or cell is 100% of SOC that means battery or cell is fully charged or a battery or cell is 0% of SOC that means battery or cell is fully discharged.

DOD describes how deeply the battery / cell is discharged. In a full charged battery/cell DOD is zero and it is expressed by Ah. When a cell is connected with load, the amount of DOD increases with time. The cell capacity and DOD become of equal value when the cell is fully discharged.

Internal Resistance

Every single Li-Ion cell holds a small quantity of internal resistance, naturally in the order of a few milliohms. The resistance connected with the cell falls into the group of active resistance. This indicates that the rate of the resistance fluctuates with deviation in certain factors such as discharge current, SOC, temperature and cell usage. Internal resistance is specified by manufacturers so that battery can be extracted.

Challenge of Li-Ion Batteries

Capacity Loss

Li-ion battery capacity is not fixed, it fluctuates over the battery cycling life. Capacity of the battery decreases linearly with the number of charging and discharging cycles (Dubarry, 2007). Although a percentage of the capacity loss is connected with the active material loss of inside the cell. Many of the active material mechanisms are dependent on the crystallinity, microstructure and morphology of active electrode materials, which directly influence the battery cell performance [Berg, 2015]. Battery cells go under charged/discharged state because battery cell resistance increases. While charging and discharging cut-off voltage remain fixed and battery cells are charged and discharged resulting in a loss of capacity.

Temperature Effects

When Li-ion battery cells are exposed to cyclical charge and discharge, the increase in battery cell temperature is accelerated and a chemical of the battery materials become instable. For such a hazard, it is frequently recommended to have electronic protection based on the battery cell threshold voltage (Taracson & Armand, 2001). If the temperature of a Li-Ion battery is not controlled, it may catch fire if temperature crosses the manufacturer specified temperature limit. If the battery cells operate in too hot or cold temperature, it results in loss of capacity and decreasing of the lifetime.

Cell Imbalance

Battery is an electrochemical device which converts chemical energy into electrical energy or vice versa. The performance of the battery depends on the chemical reaction during charging and discharging. Energy storage capacity diminishes gradually due to chemical degradation during chemical reaction. During the charging and discharging, battery cells become imbalanced. Because of this imbalance, battery life is reduced. The effect of imbalance is shown in Figure 1.7.

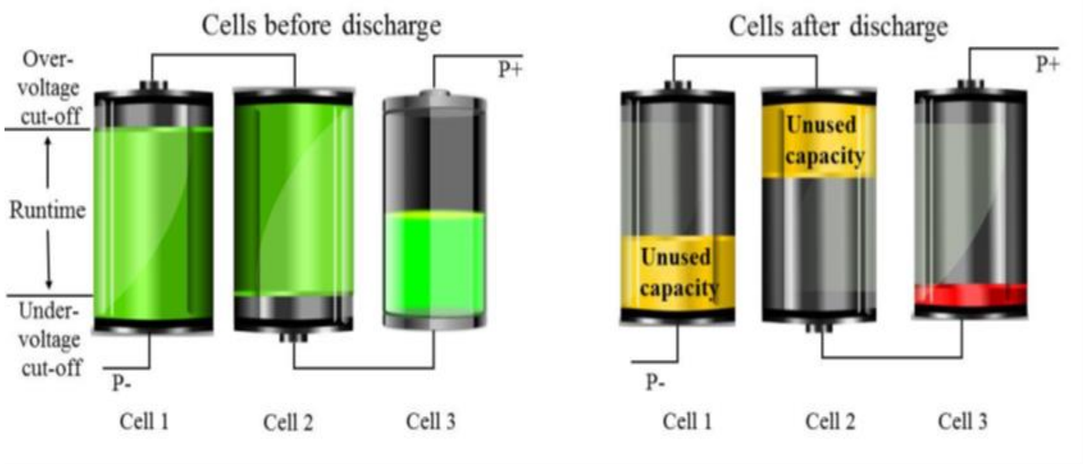

Figure 1.6 Imbalance cells (Shamsi, 2016)

Researchers are working and focusing on Li-ion batteries because of its effective features such as, high power capacity, high energy density, high power, non-memory effect, long life cycle, low self-discharge rate, and high temperature tolerance, reliability and stability for EV as these characteristics increase vehicle driving range and enhance utility. However, Li-ion battery cells decline when over-charged beyond charging limit or exhausted below minimum limits. For example, the lower and upper limits of Lithium iron phosphate (LiFePO4) are 2.7 V and 4.3 V respectively. Battery pack of EV is charged by external electric power supply and discharged by the EV driving system's power demands. It is understandable that State of Charge (SOC) and State of Discharge (SOD) of the battery pack need to be maintained at tolerable points. It is required that battery cell temperature need to kept within a preferred range and battery cells be prevented from overcharging (hazard from fire) and over-discharging (permanent cell damage). During the over discharging, the battery cells temperature increases because of the chemical degradation occurring inside the cells and unbalancing the charge. The development of EV system demands for long battery life, high voltage, high power, small battery size and high efficiency. Therefore, EV battery system requires a battery cells charge balancing system which is able to preserve the battery cells' charge, increase the cell efficiency, life cycle and perform in charging and discharging condition.

The Battery Management System (BMS) for PHEV, HEV and EV contains the following sections:

a) Voltage/charge balancing System

b) Thermal Management System

c) Protection System.

Thermal Management System improves by evaporative cooling, liquid cooling or air cooling to maintain the battery cells temperature in the scale of 40-60^{o} C. The battery protection system can be improved by appropriate electric circuit design with relay, fuse and circuit breaker. Voltage balancing system is the most essential part for the BMS and life time.

There are many voltage balancing schemes applied in BMS which have been reported in several research works on the enhancement of performance in term of long battery life, long charging cycle, high efficiency and give protection for damage cells from over-charging and under-charging condition. Based on the features of the standing voltage balancing system, the voltage balancing scheme can be categorized into energy consumption by passive component and energy transfer from cell to cell. Energy consuming voltage balancing scheme can be considered as a passive balancing method because of the excessive energy of the stronger battery cell is dissipated by the resistor in the form of heat and is balanced with lower battery cell. Another voltage balancing method is called active balancing system because of the excessive energy of the higher energy storage cell is transformed into lower energy storage cell by the capacitor, inductor/ transformer or different types of converter.