ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Birand ERDOGAN

ACTIVE BALANCING SYSTEM FOR LARGE BATTERY PACK

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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We certify that the thesis titled above was reviewed and approved for the award of degree of the Doctor of Philosophy by the board of jury on 20/07/2020

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ABSTRACT

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ACTIVE BALANCING SYSTEM FOR LARGE BATTERY PACK

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Nowadays, the tendency towards electric vehicles is increasing and various studies are being carried out in order to eliminate the shortage of battery life. One way to improve battery life is to overcome imbalances in battery packs. The imbalances due to structural differences arising from production and changing operating conditions, reduces the utilization of available energy. Passive and active equalization methods are preferred in order to overcome these imbalances. Due to the slow equalization and energy inefficiency of passive balancing circuits, the trend towards active balancing circuits is increasing. In this thesis, an active cell balancing model and a new active cell balancing algorithm that is able to transfer excess energy to the cells with weak energy via the charge transfer-bus (CTS) is proposed for a electric heavy commercial vehicle (EHCV) equipped with large battery packs (LBPs). To test and evaluate the performance of the active balancing system (AcBS), an active balancing circuit (AcBC) that includes 11 modules which consist of 16 cells equipped with bidirectional dc-dc converters and switch matrixes have been simulated in MATLAB/SIMULINK environment. The study has been carried out in two stages. In the first study, a model is presented for LBPs which can be applied in EHCVs. CTS is used for transferring excess charge from source cell to destination cell. Unlike topologies in literature, presented model doesn't need for external storage element because it uses the existing vehicle battery to buffer the CTS. The presented LBP model consists of 176 cells connected in series. Thus, twenty-two bidirectional dc-dc (BiDC) converters are used in the simulation because every 8 cells are combined with one dc-dc converter. Controlling the switching signals of BiDC converters involves high runtime/complexity. Therefore, current sources are used instead of dc-dc converters by simplifying the model in the simulation. In the second study, a new balancing algorithm is proposed. Compared to existing approaches, the algorithm with features of fast balancing, smaller voltage imbalance range, and multiple charge transfers is suitable for LBPs. By comparing the proposed algorithm with the existing algorithm, the presented algorithm has been shown to have better results for LBPs.

Key words: Active balancing, large battery pack, heavy electric vehicle.

ÖZ

YÜKSEK LİSANS TEZİ

BÜYÜK PİL PAKETİ İÇİN AKTİF DENGELEME SİSTEMİ

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Günümüzde elektrikli araçlara yönelik eğilim artmakta ve pil ömrünün kısalmasını önlemek için çeşitli çalışmalar yapılmaktadır. Pil ömrünü uzatmanın bir yolu, batarya paketlerindeki dengesizliklerin üstesinden gelmektir. Üretimden ve değişen çalışma koşullarından kaynaklanan yapısal farklılıklardan oluşan dengesizlikler, mevcut enerjinin kullanımını azaltır. Bu dengesizliklerin üstesinden gelmek için pasif ve aktif dengeleme yöntemleri tercih edilmektedir. Pasif dengeleme devrelerinin yavaş dengelemesi ve enerji verimsizliği nedeniyle, aktif dengeleme devrelerine yönelik eğilim artmaktadır. Bu tezde, büyük ölçekli batarya paketleri ile donatılmış ticari bir ağır elektrikli araç için, yük transfer barası (CTS) aracılığıyla fazla enerjiyi zayıf enerjili hücrelere aktarabilen bir aktif hücre dengeleme modeli ve yeni bir aktif hücre dengeleme algoritması önerilmektedir. Aktif dengeleme sisteminin (AcBS) performansını test etmek ve değerlendirmek için, çift yönlü dc-dc dönüştürücüler ve anahtar matrisleri ile donatılmış 16 hücreden oluşan 11 modül içeren bir aktif dengeleme devresi (AcBC) MATLAB / SIMULINK ortamında simüle edilmiştir. Çalışma iki aşamada gerçekleştirilmiştir. İlk çalışmada, ticari elektrikli araçlara uygulanabilen büyük ölçekli batarya paketleri için bir model sunulmuştur. Yük transfer barası, fazla yükü kaynak hücreden hedef hücreye aktarmak için kullanılır. Literatürdeki topolojilerin aksine, sunulan modelin harici depolama elemanına ihtiyacı yoktur çünkü yük transfer barasını tamponlamak için mevcut araç aküsü kullanılmıştır. Sunulan büyük ölçekli pil paketi modeli seri bağlı 176 hücreden oluşmaktadır. Bu nedenle, simülasyonda yirmi iki çift yönlü dc-dc dönüştürücü kullanılmalıdır çünkü her 8 hücre bir dc-dc dönüştürücü ile birleştirilir. Çift yönlü dc-dc dönüştürücülerin anahtarlama sinyallerinin kontrol edilmesi yüksek çalışma zamanı / karmaşıklık gerektirir. Bu nedenle, simülasyondaki modeli basitleştirerek dc-dc dönüştürücüler yerine akım kaynakları kullanılır. İkinci çalışmada yeni bir dengeleme algoritması önerilmiştir. Mevcut yaklaşımlarla karşılaştırıldığında, hızlı dengeleme, daha küçük voltaj dengesizliği aralığı ve çoklu şarj transferleri özelliklerine sahip algoritma, büyük ölçekli batarya paketleri için uygundur. Önerilen algoritmayı mevcut algoritma ile karşılaştırarak, sunulan algoritmanın büyük ölçekli pil paketleri için daha iyi sonuçlar verdiği gösterilmiştir.

Anahtar Kelimeler: Aktif dengeleme, büyük batarya paketi, ağır elektrikli araç.

GENİŞLETİLMİŞ ÖZET

Günümüzde ulaşım sektörüne olan önem her geçen gün daha da artmakta olup fosil yakıtlara alternatif olarak taşınabilir enerji kaynaklarının kullanımı konusunda çalışmalar yapılmaktadır. Şarj edilebilir pillerin kullanılmakta olduğu elektrikli ve hibrit elektrikli araçlara olan ilgi, ulaşımın geliştirilmesinde önemli bir rol oynamaktadır. Son zamanlarda, bu tarzdaki araçlarda enerji depolamak için yüksek enerji/güç yoğunluğu, uzun çevrim ömrü gibi faktörler nedeniyle diğer şarj edilebilir piller yerine lityum iyon piller kullanılmaktadır.

Elektrikli ve hibrit elektrikli araçlarda yüksek güçlü uygulamalar gerektiğinden, tek bir lityum iyon hücrenin voltajı sınırlı olduğu için yüksek çalışma voltajı gereksinimini karşılamak için akü modülleri/hücreleri seri olarak bağlanır. Aynı özelliklere sahip hücrelerde bile, çevre koşulları ve iç direnç, kendi kendine deşarj oranı ve kaçak akım farklılıkları gibi çeşitli nedenlerden dolayı kullanılabilir enerjiyi azaltan dengesizlikler zamanla ortaya çıkabilmektedir. Paketteki piller arasındaki bu dengesizlikler, şarj ve deşarj işleminin erken sonlandırılması ve paketteki performansın düşmesi gibi olumsuz sonuçlara yol açabilmektedir. Hatta aşırı şarjlı veya aşırı deşarj olmuş pil hücrelerinde kalıcı hasara bile yol açabilmektedir.

Pil paketlerindeki dengesizlikler genel olarak üç ana kategoriye ayrılmaktadır. Bunlar yük durumu dengesizliği, empedans farklılıkları ve toplam kapasite farklılıklarıdır. Yük durumu dengesizlikleri, elektrokimyasal karakteristikler, aşırı yük / aşırı deşarj, dengeleme devrelerindeki dengeleme akımı gibi nedenlerden oluşur. Empedans farklılıkları, kulombik verim ve pil yaşlanmasındaki farklılıklar nedeniyle ortaya çıkmaktadır. Toplam kapasite farklılıkları, modül içindeki hücrelerin farklı özellikleri ve ilk şarj kapasitesindeki farklılıklar nedeniyle oluşmaktadır.

Pil paketlerindeki dengesizlik sorunuyla başa cıkabilmek için çeşitli dengeleme topolojileri ve kontrol algoritmaları hakkında araştırmalar yapılmakta olup aktif ve pasif dengeleme olmak üzere iki ana kategoriye ayrılmaktadır.

Pasif dengeleme yöntemi, düşük maliyet avantajı nedeniyle hala pil yönetim sistemlerinde en yaygın kullanılan yöntemlerden biri olup, çalışma prensibi basittir. Bu çalışma prensibine göre, diğer hücrelere göre daha yüksek gerilime sahip hücredeki fazla enerji, dengeleme sağlamak için dirençler aracılığıyla ısı olarak boşa harcanmaktadır. Ayrıca pasif dengeleme hem şarj hem de deşarj olarak kullanılamaz. Sadece şarj işlemi sırasında uygulanır. Geleneksel hücre dengeleme yaklaşımları pasif dengeleme yöntemi olup yüksek şarj durumuna sahip hücrelerin aşırı yükü bir direnç boyunca ısı olarak dağıtıldığından dolayı enerji verimliliğinde düşüşe neden olmaktadır. Bu yöntemde, direnç her bir hücreye paralel yerleştirilir ve direnç boyutu denge oranını belirler.

Buna karşılık, aktif dengeleme devreleri, daha yüksek şarj durumuna sahip hücrelerden daha düşük şarj durumuna sahip hücrelere enerji aktararak pil voltajlarını eşitler ve hem şarj hem de deşarj işlemleri sırasında çalıştırılabilir. Akü hücrelerinin ömrünün uzatılması ve daha iyi performans göstermesi gibi nedenlerden dolayı günümüzde aktif dengeleme yöntemleri daha çok tercih edilmektedir. Ek olarak aktif dengeleme yöntemleri hem şarj hem de deşarj durumlarında uygulanabilmekte olup, dengeleme işlemi sırasında oluşabilecek enerji israfı, aktif dengeleme yöntemi kullanılarak önlenebilmektedir. Çünkü fazla enerjiyi direnç üzerinden ısı olarak harcamak yerine düşük enerjili hücrelere aktarır. Aktif dengeleme teknikleri hücre bypass, hücreden hücreye, hücreden pakete, paketten hücreye ve hücreden pakete paketten tekrar hücreye olmak üzere beşe ayrılır.

Hücre bypass eşitleme yöntemleri, maksimum / minimum voltajlarına ulaşan hücrelerin akımını bypass eder ve kalan hücrelerin de maksimum / minimum voltaja ulaşmasını bekler. Bu yöntemin uygulanması kolaydır ve aynı zamanda maliyet olarak da uygundur ancak mevcut kontrol stratejileri sadece şarj / deşarj işleminin sonunda verimlilik düşük olduğunda kullanılmasına izin verir.

Hücreden hücreye yönteminde paket koşulları önemlidir. Hücre-hücre varyasyonları, pildeki şarj durumu ve sağlık durumu tahminini etkiler ve pil yönetim sistemi kontrol performansını düşürür. Ayrıca bu pil paketlerinde termal gradyan da vardır çünkü gerçekte pil paketleri birçok hücreyi barındırır. Hücreden hücreye yöntemlerinde, hücrelerde depolanan fazladan enerjiyi, daha düşük depolanmış enerjiye sahip komşu hücrelere geçirir. Daha yüksek verimlilik göstermelerine rağmen balanslama süresini yavaş olup kontrol karmaşıklığı fazladır.

Hücreden pakete yöntemlerinde, enerji paket içindeki en fazla yüke sahip hücreden çıkar ve paket terminalleri aracılığıyla tüm hücrelere eşit olarak verilir. Bu yöntem, ısınmaya neden olmasına rağmen ekstra yük hücreden paketteki diğer hücrelere eşit şekilde dağıtıldığından, ısı şeklinde hiçbir enerji kaybı olmaması açısından güvenlidir. Paketten hücreye yöntemlerinde, paketten enerjiyi en az yüklü hücreye aktarılmaktadır. Bu yöntem, tüm şarj işlemi boyunca denge yükünün korunmasını ve hiçbir yükün kaybolmamasını sağlamaktadır.

Hücreden pakete paketten tekrar hücreye yöntemleri, hem hücreden pakete hem de paketten hücreye yöntemlerini uygulayarak enerji aktarır. Hücreden hücreye, hücreden pakete, paketten hücreye ve hücreden paketten hücreye yöntemlerinde, DC / DC dönüştürücülere dayalı geleneksel topolojiler karmaşık ve pahalı olma eğilimindedir. Bu topolojiler genellikle, paketin güvenliği ve uzun ömürlülüğü için önemli olan pil hücrelerinin aşırı şarj edilmesini veya aşırı deşarjını önlemede etkilidir.

Aktif dengeleme topolojileri kapasitör, indüktör/transformatör ve güç dönüştürücüsüne dayalı topolojiler olmak üzere üç ana kategoriye ayrılır. Kapasitor bazlı aktif dengeleme topolojileri, yapılan işlemin yüksek voltaj / şarj durumundaki hücrenin aşırı enerjisini düşük voltaj / şarj durumundaki hücreye aktarmak için kapasitörlerin harici bir enerji depolama cihazı olarak kullanılmasına dayalıdır. Literatürde tek anahtarlamalı kapasitör yapıları, çift katmanlı anahtarlamalı kapasitör yapıları bu topolojiye örnektir.

İndüktör tabanlı aktif dengeleme topolojileri, indüktörleri kullanarak hücreler arasında enerji aktarır ve kapasitör dengelemesine kıyasla hızlı dengeleme süresine sahiptir. Bununla birlikte, daha yüksek maliyet ve manyetik kayıplar bu tekniğin dezavantajları olarak değerlendirilmektedir. Transformatör bazlı aktif dengeleme tekniğinde, enerji anahtarlamalı transformatör vasıtasıyla hücreler arasında aktarılır. Literatürde, tek sargılı transformatör, çok sargılı transformatör ve modüler çok sargılı transformatör bazlı aktif dengeleme topolojileri mevcuttur.

Dönüştürücü tabanlı aktif dengeleme topolojilerinde genellikle, güç dönüştürücü ve anahtarlama durumlarını kontrol ederek enerji transferi yüksek enerjili hücreden pil paketine ve pil paketinden düşük enerjili hücreye aktarılır. Cuk, boost, buck-boost, resonant dönüştürücü, flyback dönüştürücüler, dönüştürücü tabanlı aktif dengeleme topolojierinin başlıcalarıdır. Bu topolojilerde genellikle, dönüştürücüler aracılığıyla enerji aktarımı sağlamak için harici bir şarj ünitesi gereklidir. Bu tez çalışmasında 2 çalışma söz konusudur. Birinci çalışmada pil paketindeki ilk modülün ilk hücresinin harici devre ve enerji depolama birimi yerine şarj aktarım veriyolu olarak kullanıldığı farklı bir yaklaşım önerilmektedir. Topoloji olarak her bir modül için iki adet çift yönlü dc-dc dönüştürücü ve anahtar matrisi MATLAB-Simulink ortamında tasarlanıp performansı analiz edilmiştir. İkinci çalışmada yeni bir dengeleme algoritması üzerinde çalışılmıştır ve topoloji olarak birinci aşamadaki topolojiden farklı olarak pil paketine harici bir devre olarak 24 voltluk araç aküsü bağlanmış olup, bu araç aküsünden geçen akım sıfırdır. Böylelikle araç aküsünün de ömrüne katkı sağlanmıştır. Büyük pil paketlerinde daha hızlı balanslama yapılabilmesi için eş-zamanlı şarj transferi, çift yönlü güç akışı, komşu olmayan hücreler arasında veya paketler arasında şarj transferi gibi birçok özellik, tasarlanan bu yeni algoritma ile uyumludur. Kısaca elektrikli araçlardaki büyük pil paketlerinde daha hızlı balanslama yapılabilmesi için sisteme yeni bir dengeleme algoritması eklenmiş olup, tezde önerilen kontrol algoritmasının hızlı olduğunu test etmek için başka bir algoritma ile kıyaslama yapılmıştır.

EXPANDED SUMMARY

Today, the importance for the transportation sector is increasing day by day and studies are being carried out on the use of portable energy sources as an alternative to fossil fuels. The interest in electric/hybrid electric vehicles, where rechargeable batteries are used, plays an important role in the development of transportation. Recently, lithium-ion batteries have been used to store energy in such vehicles due to factors such as high energy / power density and long cycle life.

Since high power applications are required in electric/hybrid electric vehicles, battery modules / cells are connected in series to meet the high operating voltage requirement as the voltage of a single lithium ion cell is limited. Even in cells with the same properties, imbalances that reduce usable energy may occur over time due to various reasons such as environmental conditions and internal resistance, self-discharge rate and leakage current differences. These imbalances between the batteries in the package can lead to negative consequences such as early termination of the charge and discharge process and reduced performance in the package. It can even cause permanent damage to overcharged or over-discharged battery cells.

Imbalances in battery packs generally fall into three main categories. These are SOC imbalance, impedance differences and total capacity differences. SOC imbalances are caused by electrochemical characteristics, overload / over discharge, balancing current in balancing circuits. Impedance differences arise due to differences in coulombic efficiency and battery aging. Total capacity differences occur due to the different characteristics of the cells in the module and differences in the initial charge capacity.

In order to deal with the imbalance problem in battery packs, researches are conducted on various balancing topologies and balancing algorithms, and they are divided into two main categories: active and passive balancing.

The passive balancing method is still one of the most widely used methods in battery management systems due to its low cost advantage, and its working

principle is simple. According to this working principle, the excess energy in the cell, which has a higher voltage than other cells, is wasted as heat through resistors to provide balancing. Also, passive balancing cannot be used as both charge and discharge. It is applied only during the charging process. Conventional cell balancing approaches are passive balancing methods, resulting in a decrease in energy efficiency as the overload of cells with high charge is distributed as heat across a resistance. In this method, the resistance is placed parallel to each cell, and the resistance dimension determines the balance ratio.

In contrast, active balancing circuits transfer energy from cells with a higher charge state to cells with a lower charge state, equalizing battery voltages and can be operated during both charge and discharge processes. Due to reasons such as prolonging the lifespan of batteries and performing better, active balancing methods are more preferred today. Additionally, active balancing methods can be applied in both charge and discharge situations, and energy waste that may occur during the balancing process can be prevented by using the active balancing method. Because instead of spending excess energy as heat over resistance, it transfers it to low-energy cells. Active balancing techniques are divided into five: cell bypass, cell to cell, cell to pack, pack to cell, and cell to pack to cell.

Cell bypass synchronization methods bypass the current of cells that reach their maximum / minimum voltage and wait for the remaining cells to reach maximum / minimum voltage. This method is easy to implement and is also cost-effective, but current control strategies allow it to be used only when efficiency is low at the end of the charge / discharge process.

Package conditions are important in the cell-to-cell method. Cell-to-cell variations affect battery charge and health status prediction, and BMS reduces control performance. There are also thermal gradients in these battery packs because the battery packs actually contain many cells. In cell-to-cell methods, it transfers the extra energy stored in the cells to neighboring cells with lower stored energy.

Although they show higher efficiency, the balancing time is slow and the control complexity is high.

In cell-to-pack methods, energy comes out of the cell with the highest load in the pack and is distributed equally to all cells through the packet terminals. This method is safe in that there is no energy loss in the form of heat, since the extra load is evenly distributed from the cell to the other cells in the package, although it causes warming. In pack-to-cell methods, energy from the pack is transferred to the least loaded cell. This method ensures that the balance load is maintained and no load is lost during the entire charging process.

It transfers energy from cell to pack by applying methods from pack to cell again, by applying both cell to pack and pack to cell methods. Traditional topologies based on DC / DC converters tend to be complex and expensive in cell-to-cell, cell-to-pack, pack-to-cell, and cell-to-pack methods. These topologies are often effective in preventing overcharging or over-discharging of battery cells, which are important for the safety and longevity of the pack.

Active balancing topologies are divided into three main categories: capacitor, inductor / transformer and power converter based topologies. Capacitor-based active balancing topologies are based on the use of capacitors as an external energy storage device to transfer the excess energy of the cell in the high voltage / charging state to the cell in the low voltage / charging state. In the literature, single switched capacitor structures, double layer switched capacitor structures are examples of this topology.

Inductor-based active balancing topologies transfer energy between cells using inductors and have fast balancing time compared to capacitor balancing. However, higher costs and magnetic losses are considered the disadvantages of this technique. In transformer-based active balancing technique, energy is transferred between cells by means of a switched transformer. In the literature, there are active balancing topologies based on single winding transformer, multi winding transformer and modular multi winding transformer.

In converter-based active balancing topologies, energy transfer is transferred from the high energy cell to the battery pack and from the battery pack to the low energy cell, usually by controlling the converter and switching states. Cuk, boost, buck-boost, resonant converter, flyback converter are the main types of these active balancing topologies. In these topologies, an external charging unit is usually required to transfer energy through converters. There are two studies in this thesis. In the first study, a different approach is proposed in which the first cell of the first module in the battery pack is used as a charge transfer bus instead of the external circuit and energy storage unit. As a topology, two bidirectional dc-dc converters and key matrices for each module were designed in MATLAB-Simulink environment and their performance was analyzed. In the second study, a new balancing algorithm was investigated and as a topology, unlike the topology in the first study, a 24 volt vehicle battery was connected to the battery pack as an external circuit, and the current passing through this vehicle battery is zero. This contributed to the life of the vehicle battery. Many features such as simultaneous charge transfer, bi-directional power flow, charge transfer between adjacent cells or between packs for faster balancing in LBPs are compatible with this new algorithm. In short, a new balancing algorithm has been added to the system for faster balancing in LBPs in EVs, and a comparison has been made with another algorithm to test that the control algorithm proposed in the thesis is fast.

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LIST OF SYMBOLS AND ABBREVIATIONS

EV	: Electric Vehicle
BMS	: Battery Management System
UPS	: Uninterrupted Power Supplies
SOA	: Safe Operating Area
LiPo	: Lithium-Ion Polymer
Li-CO	: Lithium Cobalt Oxide
Li-MO	: Lithium Manganese Oxide
Li-NMC	: Lithium Nickel Manganese Oxide
Li-S	: Lithium Sulfur
Li-IP	: Lithium Iron Phosphate
AC	: Alternating Current
DC	: Direct Current
PWM	: Pulse Width Modulation
LBP	: Large Battery Pack
AcBS	: Active Balancing System
AcBC	: Active Balancing Circuit
BiFLC	: Bidirectional Flyback Converter
CTB	: Charge Transfer Bus
EHCV	: Electric Heavy Commercial Vehicle
BiDC	: Bidirectional Dc-Dc
SC	: Switched Capacitor
SSC	: Single Switched Capacitor
DTSC	: Double-Tiered Switched Capacitor
MSC	: Modularized Switched Capacitor
DOD	: Depth of Discharge
SwM	: Switch matrix
SOC	: State of Charge

SOH	: State of Health
SOT	: State of Temperature
OCR	: Optical Character Recognition
IGBT	: Insulated-Gate Bipolar Transistor
Volt	: V
Ampere	: A
Watt	: W
Kilowatt	: kW
Ampere-Hour	: Ah
C	: Filling Capacity

1. INTRODUCTION

1.1. Background, Problem Determination and Research Motivation

The search for an alternative to fossil resources has been the subject of ongoing studies, as the dependence on fossil fuels has increased steadily both in the electricity generation, transportation sector and heating, and these resources have limited reserves in nature. Treaties on an international scale have been made in order to reduce the harm caused to nature while producing and consuming fossil fuels. Alternatively, the use of renewable energy sources has an important place in the energy policies of the countries. EVs have been on the agenda as an alternative to vehicles that use fuel in the automobile sector since the first day of the industry.

Although it is thought that research and developments on EVs have gained momentum due to the depletion of greenhouse gas and oil reserves, the beginning of the development of EVs is based on the 18th century (Chan, 2013). In the 19th century when fossil fuels were dominated, the foundations of the first EV were laid by Michael Faraday in 1821 (Handy, 2020). Michael Faraday was the first to understand these findings on EV basics. According to Michael Faraday, if a magnetic pole can be isolated, it must move in a continuous circle around a current-carrying cable. Faraday began to understand the work of Ørsted and Ampère in 1821, using a small mercury bath based on his own experience. This device, which converts electrical energy into mechanical energy, was the first electric motor (Anonymous1). Faraday's electric motor was proof that the movement could be provided with electricity and invited all researchers to create a world of research for electromagnetism. This engine led to the design of advanced motors seen in electrical appliances used in the construction site today (Anonymous2). After Faraday's invention of the electric motor, the introduction of electric technologies into human life has gained speed.

However, there were some basic obstacles to the prevalence of electric cars. The first was the range problem. Conventional vehicles traveled about 500-600 kilometers with full tank fuel, while EVs mostly used lead-acid or nickel-cadmium, whose range was difficult to see 45 kilometers. The second problem was the length of the charging time and the uncommon charging stations. Although it took several minutes to fill the tank of a gasoline vehicle, it took approximately 5-8 hours to fully charge an EV. Taking the electric car with an insufficient range to places where there is no one-charge charging network has been a problem for consumers accustomed to using the widespread gas station network for years. Another obstacle was that the battery used in electric cars increased the vehicle price compared to its fossil fuel competitors. For the price of the battery to drop, the production of EVs had to take a massive dimension (Ustabaş, 2014).

After 1990, new battery technologies emerged in the context of fuel saving and environmental protection. One of the biggest problems in new battery technologies in EVs is not having enough battery usage times. Studies to extend the life of the usage of battery are usually research on equalizing the cell voltage in the battery group (battery module). A battery module consist of many cells connected in seriesand Imbalance between cells can occur for different reasons. These can be external reasons arising from use and reasons arising from production. Causes such as protective covers which cause different amounts of charging current to be drawn from the cells in the same package, and different areas of the package to be heated differently are sources of use. Production differences and differences in cell impedance are causes arising from production. The longevity of the batteries' life are possible by the equalization of all cell voltages in a battery module. Because the cell with the lowest voltage in the battery module determines the discharge point of a battery, a low voltage cell causes the life of the entire battery module to decrease. The high voltage cell during charging causes loss of balance in the battery and does not allow the low voltage cell to be fully charged. At this point, battery balancing systems try to keep the voltage level of each cell, and therefore its capacity, closest to each other, thereby extending the life of the battery group. In short, Cell voltage imbalances caused by different reasons are balanced by various cell voltage balancing methods. Although passive balancing methods were used to eliminate imbalances in the battery, active balancing method was used in this study because it performed faster balancing process.

Our research motivation in this thesis is to present an original algorithm that eliminates battery imbalances with having faster balancing features such as energy transfer between battery modules simultaneously/nonneighbor balancing and to use the algorithm in a real EHCV in the future.

1.2. Subject and Aim of This Thesis

The subject of the thesis is the overcome the imbalances in battery modules. The purpose of the thesis is modelling an active balancing topology that provides fast equalization for LBPs and to interpret the results obtained from new algorithm which is presented by us. To test the system, AcBC model which has features like non-neighbor balancing and concurrent charge transfer process is simulated by using Matlab/Simulink. Presented AcBS consists of eleven modules and each module has two bidirectional dc-dc converters equipped with switch matrices. Since controlling gate signals in BiDC converters requires high run-time and more complexity, BiDC converter circuit is modeled using current sources. In short, an AcBS has been designed for battery modules used in EHCVs and a new balancing algorithm which is adapted to eleven battery modules with fast balancing time is researched. In other words, main purpose of this study is to present a system that performs fast balancing, has a unique balancing algorithm which is applied easily by switching rule. In addition, it is seen in chapter 5 that presented model is more economical compared to other active balancing topologies in the literature when adapted for LBPs.

After the introduction of the problem statement, research motivation and contribution of the research, the structure of this thesis is as follows.

In the second part, information about battery technology, the heart of EVs, is given. Subjects such as battery types used in EVs, battery parameters, comparison of battery types are presented.

In chapter three, battery management system (BMS) for EVs are introduced, important BMS parameters are presented, and general information about cell equalization methods are mentioned. In addition, basic informations about power electronic elements and dc-dc converter topologies used in active equalization methods are given.

In the fourth chapter, literatures on active balancing topologies are given detailed and problems in EHCVs are mentioned.

In the fifth chapter, balancing system elements which are modeled in simulation program, are described. Two different active balancing models which are compatible with LBPs are presented and different control schemes are explained for both models. The reactions of the system for different situations are examined and the similarity and agreement between the expected and the obtained simulation results are examined and compared.

In the sixth chapter, a brief summary of what has been done is presented in the thesis. Innovative works topics which can be done in the future is discussed.

1.3. Outputs and Contributions of the Thesis

The main results of this thesis, its contributions and the results we obtained can be listed as follows:

i. Since there is not much work on balancing LBPs in the literature, an active balancing model is presented in the first study to equalize cell imbalances in EHCV battery packs. CTS in AcBs is fed from the first cell in the first module. Thus, there is no need for auxiliary circuit.

ii. Balancing algorithm is proposed for LBPs in the second study. Compared to existing approaches, the algorithm with features of fast balancing, smaller voltage imbalance range, and multiple charge transfers is suitable for LBPs.

iii. Compared to other topologies in the literature, AcBS presented in the thesis has less number of switches and BiDC converter so balancing model is cost-effective.

A comprehensive knowledge about the subject is done by examining, researching and comparing in detail.

2. FUNDEMENTALS OF BATTERIES USED IN EV

2.1. General Information About Battery

Devices that convert chemical energy into electrical energy and store it within its structure are called batteries. If this conversion is one-way, the battery is a primary structure, that is, a disposable or non-charged system used by the public. If the transformation can take place in both directions, that is, if the electrical energy can be converted back into chemical energy and thus energy usage can be provided for a long time, the battery is a secondary structure or in other words, it has a rechargeable feature (Anonymous3).

Although lead acid batteries are the most used type of rechargeable battery, battery technology is constantly developing and academic studies are done on new battery types (Anonymous4). However, considering the battery parameters, commercially available battery types are limited. Despite nearly 2 centuries of work, a battery that still allows widespread use of EVs has not been developed yet. However, studies on this subject are continuing rapidly. With the advancement of battery technology, the driving distance of EVs and the power range of the electric machine also change. Understanding the basic concepts in battery technology is of great importance in order to determine which battery type to choose for the application. It is also very important to master basic concepts while designing a system and creating an algorithm for the system.

2.2. Battery Parameters

The criteria to be considered for battery packs are:

*Specific Energy and Specific Power
*Energy Density
*Voltage Characteristic
*Amper-Hour Efficiency

*Energy Efficiency

*Cost

*Operating Temperature

*Battery Life

2.2.1. Voltage Value

All battery cells have a nominal voltage value. To obtain a desired voltage (higher than nominal voltage), cells are connected in series (Kundakçı, 2016).

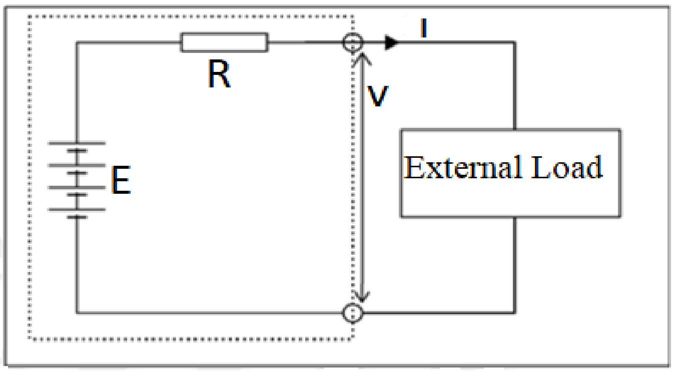

Figure 2.1. Equivalent circuit of battery (Kundakçı, 2016)

The figure above shows the equivalent circuit of battery (Fig.2.1). When battery voltage is E, the voltage on the load becomes V. Because every battery has an internal resistance. If current is expressed as I, Equation (2.1) is obtained.

$$V = E - I.R \tag{2.1}$$

If the current I is zero, the voltage V will be equal to E. Therefore E is called open circuit voltage. When the current I is given in the opposite direction, that is, during the battery filling, the V value will increase by IR (Kundakçı, 2016).

2.2.2. Charge Capacity

It is one of the most important parameters of the batteries. Battery capacity" is a measure (typically measured as Ampere-hour) of the charge stored by the battery. The battery capacity represents the maximum amount of energy that can be extracted from the battery under certain specified conditions (Anonymous4). It is assumed that a battery with the capacity of 20 amp-hours can give 20 A for 1 hour or 10 A for 2 hours (Kundakçı, 2016).

However, the actual energy storage capabilities of the battery can vary significantly from the rated capacity, as the battery capacity depends strongly on the age and past history of the battery, the charging or discharging regimes of the battery and the temperature (Anonymous4). To better understand, another important concept C (filling capacity) value should be known. It is understood that when a battery with a charge capacity of 20 Ah has a discharge current of 2C and a charging current of 0.8 C, it is necessary to apply 16A charge current that can use 40A discharge current. The nominal capacity of each electrode is expressed by the Peukert law given in Equation 2.2. The capacity of the battery is determined by the electrode which is the lowest in terms of capacity (Anonymous4).

$$C_P = {I_B}^k t \tag{2.2}$$

C_p: Capacity according to Peukert (Ah)

I_B: Battery discharge current (A)

t = Battery discharge time (hours)

k: Peukert constant

2.2.3. Stored Energy

The energy stored in a battery depends on the voltage and charging capacity of that battery, and its unit is Watt-hour. The stored energy of a battery is found by multiplying battery voltage and charging capacity (Kundakçı, 2016).

2.2.4. Energy Density

The amount of electrical energy that a battery can store per unit weight or unit volume is called energy density. It is considered as two basic concepts: gravimetric and volumetric. Although the gravimetric energy density is expressed in Wh / kg unit, it can be understood that it indicates the amount of electrical energy that can be stored in unit weight. Volumetric energy density is expressed in Wh / lt unit and indicates the amount of electrical energy that can be stored in unit volume. High energy density in batteries is a desired and targeted situation .It is used to determine the battery volume required for EV (Anonymous5).

2.2.5. Specific Energy and Specific Power

Specific energy is found by dividing the battery mass by the amount of energy stored. Its unit is $Wh.kg^{-1}$. The specific amount of power is found by dividing the power of the battery by its weight. Its unit is $W.kg^{-1}$. The specific amount of power of the battery is also related to the connected load. However, batteries operate at maximum power for a certain period of time, and operation at maximum power is not efficient. That is, high specific power results in low specific energy. Because the high current drawn from the battery in a short time will decrease the battery energy. This is an important parameter during the design of EVs. The vehicle designer should establish the balance between specific energy and specific power in the vehicles to be designed. Vehicles powered by batteries with higher specific power have higher acceleration values, while vehicles powered by batteries with high specific energy will have longer range values. For this comparison, the method known as ragone relationship and ragone plot is used. Figure 2.2 shows the ragone plot for various types of batteries. For all types of batteries, a constant is obtained from the multiplication of a force of specific power with specific energy. Equation 2.3 gives information about the characteristics of the battery when shown graphically (Kundakçı, 2016).

$$(SP)^n(SE) = \lambda \tag{2.3}$$

The letters n and λ in the equation are curve fitting constants.

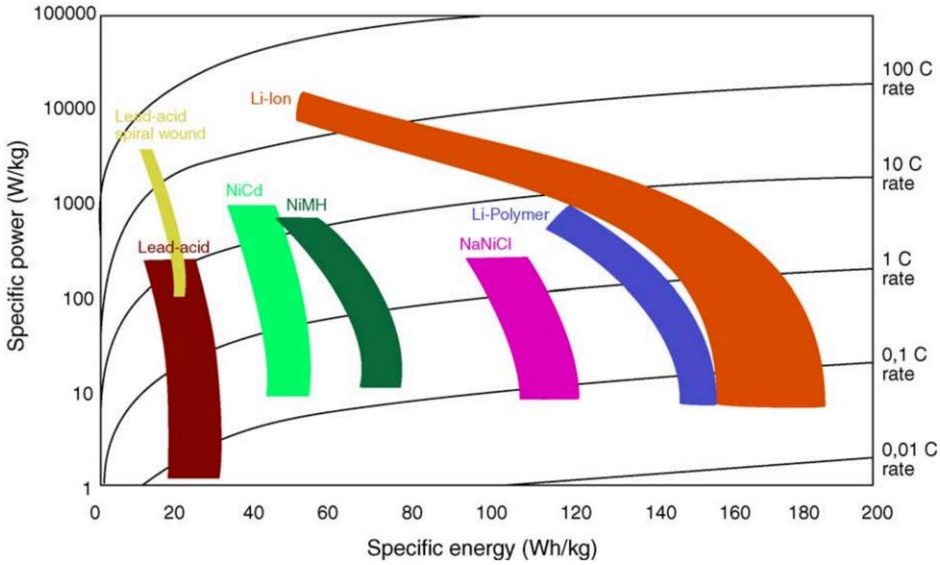

Figure 2.2. Ragone chart (Van den Bossche et al., 2006)

In the Ragone chart, the increase in the direction of specific power can be considered as the acceleration increase, and the increase in the specific energy direction can be considered as the range increase.

2.2.6. Battery Operating Temperature

There are operating temperatures that vary depending on the type of batteries. While some batteries operate at ambient temperatures, some batteries require heating for efficient operation. Some batteries also need cooling during operation. In the design of the EV, the operating temperature of the battery should be taken into consideration.

2.2.7. Discharge Depth

The discharge rate that occurs to discharge a battery from100% occupancy rate to 0% occupancy rate is called depth of discharge (DoD).

2.2.8. Cycle Life

The battery can be put into a charge/discharge “cycle” of up to a certain number so as to maintain up to 80% of the capacity specified as Ah. That number is equal to the "cycle life" of that battery. For a more general definition, the batteries experience chemical and physical deformation as long as they are charged and discharged. This deformation is called cycle life.

2.3. Battery Types Used in EVs

With the invention of EVs in 1828, the development of battery technologies has accelerated (Morimoto, 2015). EVs have become more preferred especially in recent years due to the less noisy operation and lack of carbon emissions compared to internal combustion engines. For the efficient and economical operation of EVs, a powerful battery design should be developed by developing battery technologies. Many types of batteries have been developed to solve the problems encountered in EV applications. Comparison of commonly used battery types in Figure 2.3 is given (Tarascon and Armand, 2001). Due to the increasing number of technologies that require electrical energy in the 21st century, rechargeable batteries have become indispensable for daily lives. For this reason, the most efficient rechargeable battery type has been researched and various R&D activities have been started on it.

The popular types of batteries used in EVs are as follows (Iclodean et al., 2017);

*Lead Acid Batteries

*Nickel Cadmium Batteries

*Nickel Metal Hydride Batteries

*Lithium Ion (Li-ion) Batteries

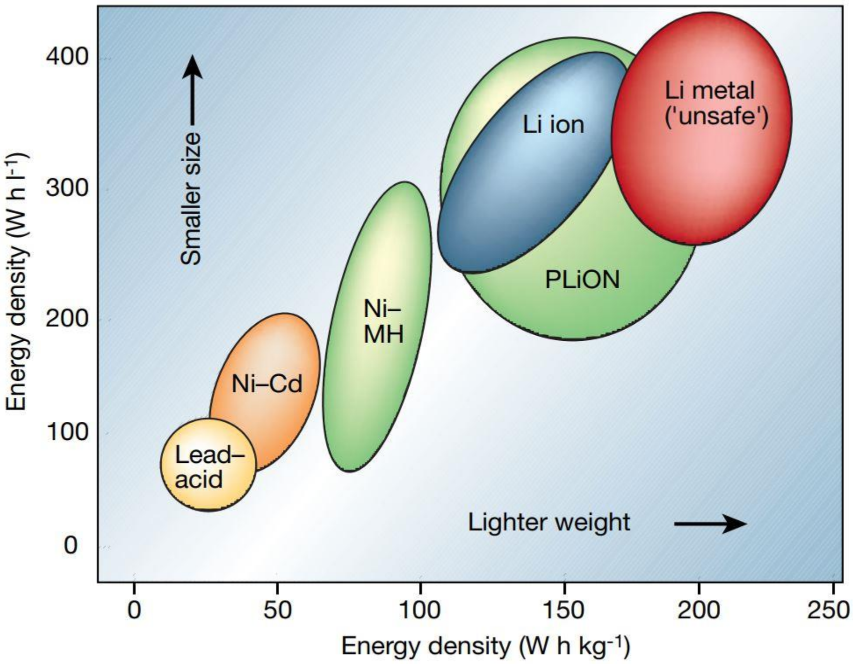

Figure 2.3. Comparison of battery types (Tarascon and Armand, 2001)

2.3.1. Lead Acid Batteries

Lead-acid batteries with an internal structure in Figure 2.4 are used in many applications in practice, also they are a very common and old type of battery. In the first EV applications, lead acid batteries, a type of rechargeable battery developed by Gaston Plante in 1859, were used (Anonymous6). In lead acid batteries, the positive plate is covered with lead dioxide metal. Negative plates are covered with lead. The electrolyte liquid is a dilute sulfuric acid solution. Sulfuric acid, lead and lead dioxide react, and releasing water and lead sulfate. Meanwhile, electrical energy is released (Demir and Kılıckan, 2018). Lead acid is economical, although dangerous. It has positive aspects such as low self-discharge, high discharge current, lack of memory effect. The life cycle is not long, rated voltages are not high enough and it has low specific energy. When these types of batteries are not used, the capacity decreases because of waiting (Baygüneş, 2019). Lead acid batteries are generally used in wheelchairs, golf cars, safety lighting and UPS. Lead acid batteries are not preferred due to the toxicity of lead and damage to the ecological system (Anonymous7). An example of a 12 V and 8Ah lead acid battery is given in Figure 2.5.

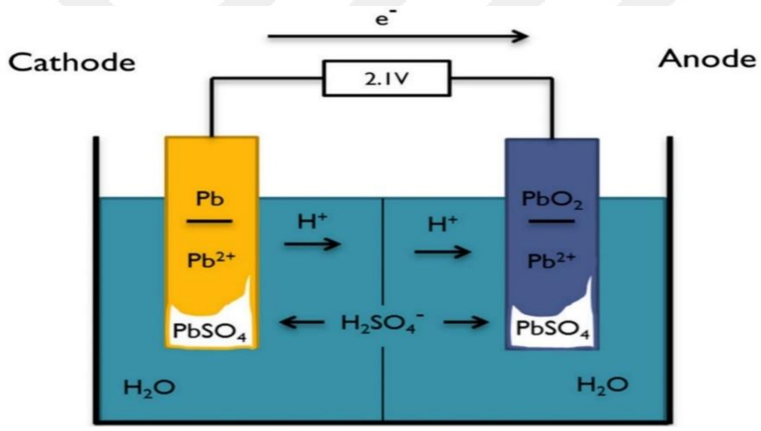

Figure 2.4. Chemical reaction of the lead–acid battery (Huang, 2015)

Figure 2.5. Lead acid battery (12V)

2.3.2. Nickel Cadmium Batteries (Ni-Cd)

Nickel cadmium batteries are also among the oldest known rechargeable batteries (Çetin, 2011). These batteries were developed in 1899. Nickel cadmium batteries are both reliable and inexpensive. When the structures of these batteries are examined, cadmium / cadmium hydroxide is used on the negative plate, nickel hydroxide / nickel oxyhydroxide is used on positive plate and potassium hydroxide (KOH) materials are used as electrolyte solution. Nickel cadmium batteries providing high discharge current have higher energy density than lead acid batteries. However, these batteries have problems such as high self discharge, low filling / discharging efficiency and having a memory effect (Anonymous7). Nickel cadmium battery is used in medical devices, electrical equipment and aviation. As they are very harmful to the environment, it has been tried to be developed with more environmentally friendly chemicals. An example of a 4.8 V/700 mAh NiCd battery group is given in Figure 2.6.

Figure 2.6. NiCd battery (4.8V)

2.3.3. Nickel Metal Hydride Batteries (Ni-MH)

By improving the negative properties of Nickel Cadmium battery, Nickel Metal Hydrate batteries were developed. It was developed by adding hydrate instead of cadmium. Ni-MH battery has higher energy density than nickel cadmium battery with the same rated voltage values. It is used as a battery system in some HEV/EV applications in today's world. Its chemistry is especially lighter and environmentally friendly than lead acid batteries (Anonymous7). It can be operated with serial cells connected to each other and can be increased to high voltages to use in EVs. Nickel Metal Hydride batteries can be expressed as 300 to 500 operating cycles (300-500 times charge and discharge). Figure 2.7 shows the battery packaging of a Toyota hybrid vehicle (Anonymous8).

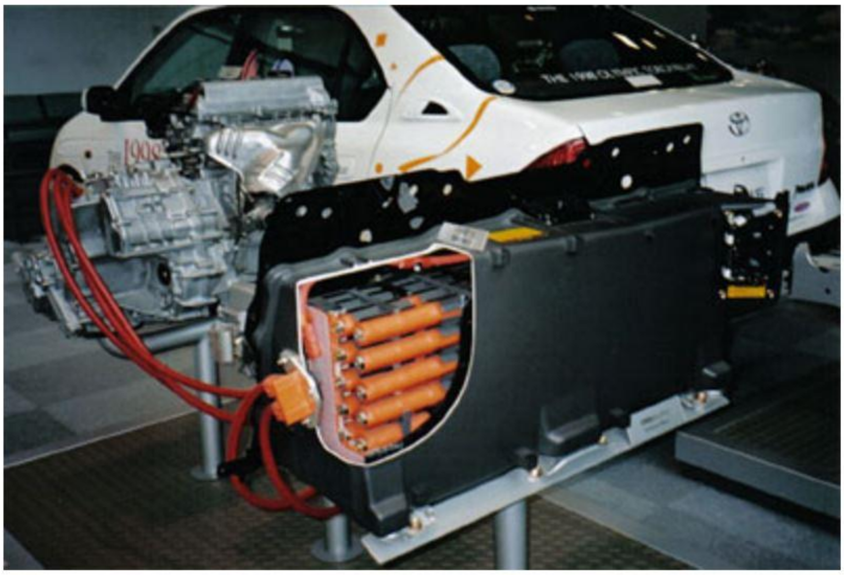

Figure 2.7. Nickel-metal-hydride battery of a Toyota hybrid car

2.3.4. Lithium Ion (Li-ion) Batteries

Batteries with lithium chemistry are generally called lithium-ions to indicate the ion exchange properties of lithium. Lithium is an ideal anode material because it is the metal with the lowest weight. In Lithium ion battery, lithium metal oxides are used as positive charged electrodes due to high heat, low toxicity and economically low cost compared to other materials. Lithium Ion battery groups which is shown in figure 2.8, is preferred instead of nickel based battery groups due to higher energy density and higher nominal voltage (Yong et al., 2015). This battery group, which is used for energy storage in most areas, especially EV applications, is preferred used due to the high energy density in parallel with the developing technology.

For example, Renault Fluence Z.E., Nissan Leaf and Ford Focus EVs are vehicles that use li-ion batteries in battery packs (Aldoğan, 2012). Although it is more expensive than other batteries, it has been the most popular type of battery because it is long-lasting and does not require much maintenance (Anonymous8).

The main advantages of lithium battery group is listed as follows (Yong et al., 2015):

1) Unlike lead acid chemistry, it does not require maintenance
2) Long life and high cycle number
3) Wide operating temperature range
4) Fast charging feature
5) Possibility to discharge with high current
6) High energy efficiency
7) High specific energy and energy density
8) Lack of memory effect

Lithium ion batteries are classified into several classes according to the materials used as positive/negative electrodes and electrolytes.

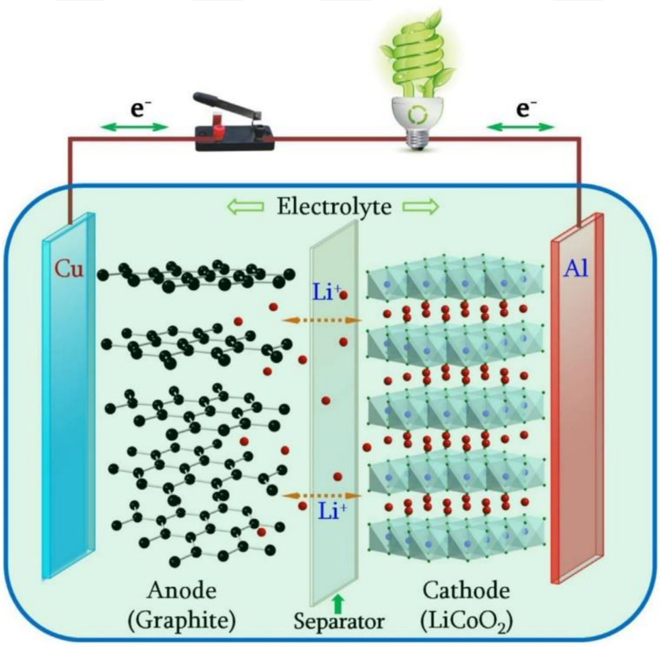

Figure 2.8. Structure of li-ion battery (Liu et al., 2016)

2.3.4.1. LiPo Batteries

Rechargeable Li-Po batteries, one of the energy sources of the future, are based on the use of compressed polymer electrolyte between cathode and anode. The cells offers the stratified structure,shape and size flexibility, which provides more advantages for portable power supply applications compared to liquid electrolyte batteries. This technology offers a potential for future low production costs. It is also environmentally friendly and avoids electrolyte leakage that will damage electronic components (Yılmaz, 2010). All of the mobile phones on the market that use Li-po type batteries are hybrid, that is, they contain gel-shaped electrolyte. LiPo battery types and Li-ion battery types show similar properties. In LiPo batteries, the structure of which is given in Figure 2.9, the polymer material as electrolyte appears as the most obvious difference between them. Polymer electrolyte is an electrically better conductor than organic liquid electrolytes. The use of polymer electrolytes allows the production of LiPO batteries quickly, easily and in different ways (Baygüneş, 2019). In recent years, interest in lithium battery powered hybrid vehicles has been increasing in world.

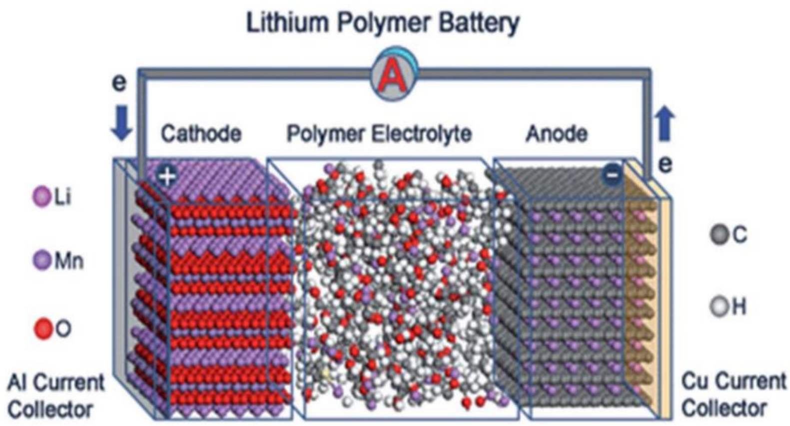

Figure 2.9. Structure of Li-Po battery (Long et al., 2016)

2.3.4.2. Li-S Batteries

With the commercialization of li-ion batteries by Sony in 1991, portable devices have become widely used worldwide. However, li-ion batteries have practically reached their theoretical capacity, so it can be said that they are entering a stationary period. In addition, the energy density of li-ion batteries is not sufficient for large-scale applications such as EVs. Energy intensity of li-ion batteries throughout the system is 100-150 Wh / kg and this value is not at a level that can compete with internal combustion engines. While the range that can be taken with a vehicle with an internal combustion engine is about 800-1000 km, the distance to be reached with a single charge of the li-ion battery remains quite low compared to this value. To increase the range of EVs, the energy density of the battery type to be used should be high. In this context, Lithium-Sulfur (Li S) batteries are a very suitable alternative especially for EV applications. During the development of battery technology for EV, lithium sulfide (Li-S) batteries have become a promising option. These batteries are the biggest candidates for batteries that can be used in EVs with their cost and unique energy density. The fact that sulfur is cheap and abundant according to the market conditions has increased the research on the use of sulfur as a cathode material nowadays. These batteries have low cell voltage, high energy density, high charging efficiency and average cycle life (Ekici, 2019). Lithium sulfide batteries do not encounter any safety problems when storing energy compared to lithium ion and lithium polymer batteries, which are frequently used in various application areas. Lithium sulfur battery cells are also light, safe and maintenance-free cells. One of the most important features of these batteries is that they can be 100% discharged (Nazar et al., 2014).

2.3.4.3. Li-IP Batteries

The Li-IP battery, whose chemical structure is seen in Figure 2.10, is a type of lithium-based battery that uses lithium iron phosphate as a positively charged electrode material. These batteries are cells with 3.5 volts full voltage, 3.3 volts operating voltage and 3.7 volts charging voltage. It is preferred in EVs with its stable working structure at high temperatures and low temperatures, it does not contain toxic substances, its charge-discharge life is long, its electrochemical performance is good, it has reliable characteristics and it has high capacity. Lithium iron phosphate batteries have an average energy density of 200 watt hours / kg. It is a type of battery with a minimum risk of explosion even during high temperature and short circuit. The number of charge and discharge is ten times that of lead acid batteries. An electronic circuit should be used, although it has a wide tolerance to charging (Ekici, 2019). Nowadays, lithium iron phosphate batteries are used extensively in electrical devices (Jones et al., 2015).

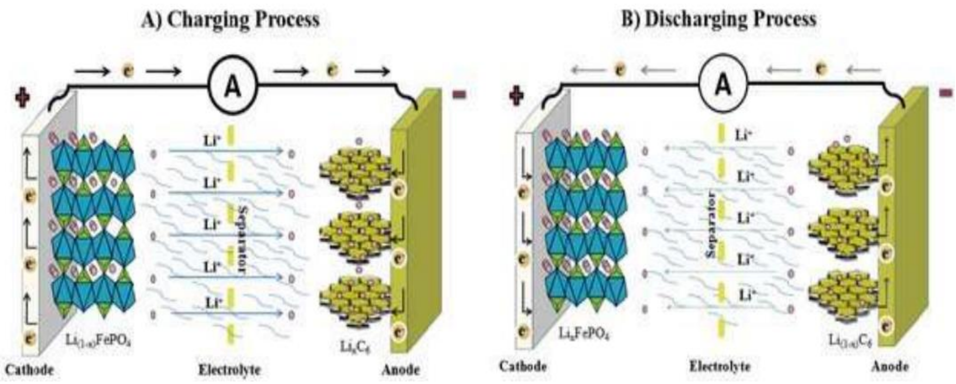

Figure 2.10. Structure of Li-IP battery (Sepasi, 2014)

2.3.4.4. Li-CO Batteries

Li-CO is a chemical generally used in positive electrode in li-ion battery. Graphite is used in negative electrode. Most lithium battery cells used for portable devices have lithium cobalt oxide chemistry because they offer high capacity per unit volume. However, due to its high reactivity and low thermal stability, Li-CO type of batteries have a high risk of fire (Anonymous9). Lithium cobalt structure is shown in Figure 2.11. Lithium cobalt oxide batteries have a short lifetime compared to other lithium-based batteries. The lifetime of the battery has been increased with the developed nickel, manganese and aluminum based batteries (Anonymous9). Cobalt is a rare element and is expensive. Therefore, it is not widely used in EVs, but still Tesco Roadster and Smart Forwto vehicles have Lithium cobalt oxide batteries.

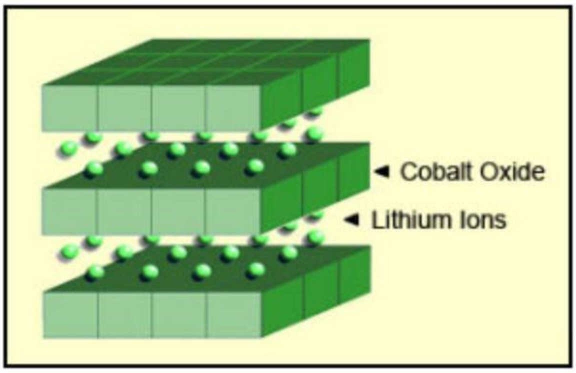

Figure 2.11. Lithium cobalt structure (Anonymous9)

2.3.4.5. Li-MO Batteries

The manganese element in the structure of lithium manganese oxide is a metal generally used in the steel industry in the production of stainless steel. In this type of batteries, the risk of explosion and flammability caused by cobalt is eliminated. Therefore, they have a very safe structure in this respect. However, with the increase in temperature, they experience serious capacity losses. For this reason, thermal management is important in lithium manganese oxide battery types. Although Li-MO batteries were first found in the 1980s, it took 15 years to become widespread and take place in the market. Lithium manganese batteries have a three-dimensional backbone structure. Thanks to this structure, ions flow more easily than the electrodes. Thus, the battery has a lower internal resistance. Low internal resistance enables fast charging and discharging at high currents. The Lithium manganese structure is shown in Figure 2.12 (Anonymous9).

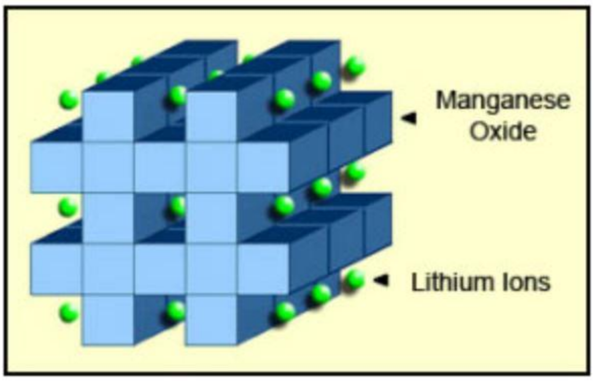

Figure 2.12. Lithium manganese structure (Anonymous9)

These battery types are used in medical devices and electric cars. The combination of Lithium manganese battery group with lithium manganese cobalt oxide battery group become new tools. These tools are used for EVs. Nissan Leaf, Chevy Volt and BMW i3 are just examples of these battery group combination (Anonymous9).

2.3.4.6. Li-NMC

One of the most successful lithium-ion battery types is Li-NMC. Like manganese batteries, it can give high current or draw. In fact, battery capacity can be increased by adding silicon instead of graphite to the anode part. However, this process ocurrs the lifetime of the battery decreases. The success of these batteries is combined with the combination of nickel and manganese. While nickel is a metal with high energy density, manganese has low internal resistance due to its spinal structure. These two elements came together to form a structure with low internal resistance and high energy density. Due to its superior features, these batteries are used in electric bicycles and other electric powertrain systems. Battery manufacturers have started to develop a nickel structure cathode by giving up the cobalt cathode structure. Nickel-type batteries cost less than cobalt. Li-NMC battery is used for power tools, e-bikes and other electric powertrains (Anonymous9).

2.4. Comparison of Batteries

Today, battery technologies with different energy density and rated operating voltage are available and these technologies are constantly being developed. Battery technologies and features that are generally used in EVs and are still in development are given in table 2.1 (Yong et al., 2015). Lithium-based batteries used in EVs in recent years offer an optimum solution to all the needs. Because of these advantages shown in table 2.2, in the thesis, lithium batteries are preferred to be simulated by using the matlab/simulink so that in the future it can be applied to experimental setup. For those who want detailed information about Battery Technology, sources (Haiying et al., 2011; Aderemi et al., 2018; Simeon et al., 2018; Ashton, 2005; Lincoln, 2000; Zhao et al., 2016; Buchmann, 1999; Anonymous11) can be examined.

Table 2.1. Comparison of EV battery types (Yong et al., 2015)

Battery type	Nominal Voltage (V)	Energy density (Wh/kg)	Volumetric energy density (Wh/L)	Specific power (W/kg)	Life cycle	Self discharge (%per month)	Memory effect	Operating temperature (ºC)	Production cost ($/kWh)
Lead acid	2	35	100	180	1000	<5	No	-15 to +50	60
Ni-Cd	1.2	50-80	300	200	2000	10	Yes	-20 to +50	250-300
Ni-MH	1.2	70-95	180-220	200-300	<3000	20	Rarely	-20 to +60	200-250
ZEBRA	2.6	90-120	160	155	>1200	<5	No	+245 to +350	230-345
Li-ion	3.6	118-250	200-400	200-430	2000	<5	No	-20 to +60	150
LiPo	3.7	130-225	200-250	260-450	>1200	<5	No	-20 to +60	150
LiIP	3.2	120	220	2000-4500	>2000	<5	No	-45 to +70	350
Li-S	2.5	350-650	350	-	300	8-15	No	-60 to +60	100-150

Table 2. 2. Advantages of lithium-ion batteries (Anonymous12)

Advantages	High specific energy and high load capabilities with Power Cells Long cycle and extend shelf-life; maintenance-free High capacity, low internal resistance, good coulombic efficiency Simple charge algorithm and reasonably short charge times Low self-discharge (less than half that of NiCd and NiMH)

3. BATTERY MANAGEMENT SYSTEM (BMS) FOR EVs

3.1. General Information about BMS

Battery technologies are widely used today, from the simplest electronic devices to EV technologies (Muratoğlu and Alkaya, 2015). In EV technologies, battery packs generally consist of serial and parallel connected cells. The desired current, voltage and capacity value of the battery vary according to these connections. The battery management system enables the serial and parallel cells to be connected to each other and to work in a coordinated and safe manner. Battery management systems are critical in EV technologies.

Battery management systems, which perform basic tasks such as calculation, data monitoring and protection, track the current, voltage and temperature of the battery with data monitoring algorithms. These values change momentarily. The calculation algorithm of the BMS interprets the instantaneous values in the monitored data and calculates the health status of the battery, battery's SOC, maximum and minimum charge / discharge current, maximum and minimum voltage, operating time and number of cycles. The values obtained from these algorithms are effective on the protection side of the BMS. The main purpose of BMS is simply keep battery module within the SOA. High / low voltage formation in the cell and battery packs is prevented, high current draw is prevented and leakage current is prevented during the charge / discharge process by the data obtained by the BMS's protection algorithm (Ekici, 2019).

One important task of the BMS is to determine the battery's state of charge obtained from the calculation algorithm and to ensure that the battery cells in the battery packs are kept in balance during charge / discharge. Every cell voltage is monitored during this process. The methods used for this balancing process will be described later in the thesis (Shen et al., 2018). In short Battery Management Systems (BMS) basically perform current and voltage inspections during the charging and discharging of the batteries. They are designed to prolong the lifespan of the batteries and increase their efficiency.

In the thesis, li-ion battery cells are used because of the advantages which are mentioned in section of the Fundementals of Batteries Used in EV. It is vital that a battery pack with lithium chemistry be controlled by the battery management system while it is being charged, and should cut off the charging current when the battery cell reaches its maximum charging voltage. Discharge should be interrupted when any cell reaches the low voltage level. This is the first function of the battery management system. If this function of the BMS is not working properly, the battery pack will be damaged. The energy storage capacity of a damaged battery pack will decrease, so the cycle time will be significantly reduced given the next cycles.

BMS should also bring the cells connected in series within the battery pack to an equal voltage level using active or passive topologies, thereby maximizing battery capacity. It also allows the maximum energy efficiency and charge amount to be maintained by keeping the cells in the battery pack at the same voltage level. In order to benefit from a battery pack with maximum efficiency, the cells forming the pack must be charged up to the maximum voltage. However, because the production process is highly dependent on chemical reactions, the cells do not behave in the same way during the charge and discharge stages. Some cells charge / discharge quickly, while others perform this process relatively slowly. Although this difference is not so noticeable during the first cycles, the differences between minor changes and voltages increase. If this situation is not prevented, various problems, especially capacity losses, will occur in a short time. Balancing systems are used to prevent the related problem.

A battery management system can perform the balancing function in two different ways. These are passive balancing and active balancing methods. However, it is important to know the bms parameters before explaining the balancing methods.

3.2. Important Parameters for BMS

Battery status controls, which have an important place in the battery management system, cannot be measured directly from the battery. For this reason, it is necessary to determine the correct battery model and make measurements on the model. There are different techniques related to battery modeling methods in the literature. These methods include analytical (experimental), statistical, electrochemical and electrical circuit models. The critical parameters for the BMS are SOC, SOH, and SOT.

3.2.1. SOC

BMS plays a significant role in storing energy in the battery to improve performance and extend battery life. Therefore, the BMS has two operational criteria as monitoring and control feature. Monitoring process is an inseparable whole with the control dimension. A fast, precise and accurate monitoring system is required to accurately control the charge/discharge processes of the batteries (Leksono et al., 2013). An ideal BMS should be efficent to achieve the full capacity of the battery and to ensure low power consumption. The BMS prevents damage to the battery due to overcharging, over-discharging or excessive power consumption (Xing et al., 2011). However, it is not easy to ensure the safe operation of the battery, since the SOC depends on the evaluation from instant data (Zahid et al., 2017).

SOC (state of charge) is defined as the current capacity of a battery, expressed in terms of its rated capacity (Xiong et al., 2017). The basic desire of a user is to know how long the battery pack will complete its discharge. For this reason, for the EV user, the most accurate way to know the remaining range of the vehicle is to calculate the SoC value. For a battery pack of lithium chemistry, it is unlikely to estimate SoC by looking at the voltage due to the voltage plateau between 20% and 80%. Instead of using voltage reading, current integration method called coulomb counting is used. Since these methods do not give correct results when used separately, the two methods are generally combined and used. A system where voltage and current integration are used together will be more successful in SoC estimation. As a result of measuring current and voltage with high resolutions, cell capacity can be determined much more accurately. SOC can be used to prevent improper operation of the batteries, thereby ensuring safety. SOC can only be estimated by analyzing the current battery's voltage, temperature, and other information regarding the battery being considered. The SOC parameter ensures that a large amount of current is not discharged if the battery's SOC is minimum and prevents extra charge when the battery's SOC is maximum. Therefore, the charge and discharge current can be programmed to follow a method depending on the SOC, and thus the battery can continue operating without damage. The chemical reaction in a battery's cells affects the current capacity of the battery, because of causing the temperature to rise. Therefore, the battery temperature should be monitored and regulated to prevent cell damage. A battery can usually be connected in series, parallel, or series-parallel combination to meet the load voltage and power requirement needed. There will be voltage imbalances between cells due to the use of different number of cells in different chemistry. Since the cells cannot be overcharged, charging should be stopped if any cell is found to be fully charged even if the remaining cells are partially charged, because, cell imbalance will occur (Ekici, 2019). This cell imbalance lowers the total capacity of a healthy battery, causing loss of capacity. Therefore, a system is needed to prevent this loss of capacity and perform cell balancing. Therefore, a unique algorithm on cell balancing topology is proposed for LBPs in the thesis.

3.2.2. SOH

The state of the batteries at the time of charge or discharge depends on the battery health condition (SOH -State of Health), known as a guarantee of safety, durability and performance, and estimating as a sequence of aging is crucial for determining the time the battery has been replaced or calculating the driving mileage unit (Park et al., 2016). SOH is related to the parameters involved in the design of the battery. It describes the degree of battery life and is reflected by loss of capacity or increased resistance (Shen et al., 2018). Unlike SOC, an exact definition of SOH has not yet been presented. Individual research is still underway on this definition. In general, in industrial applications, SOH is calculated by examining battery chemistry (Lee et al., 2016; Rong and Pedram, 2003; Ng et al., 2009). Historically, the knowledge of these variables is only moderately accurate, and this results in moderate performance. Therefore, a more conservative use is required to check the health of the batteries (Ekici, 2019).

SOH reflects the ability of a battery to store energy according to the initial conditions, taking into account the application power requirements. This estimate is unconditionally necessary to make the battery safer to use. SOH reflects the current state of the battery as a percentage and 100% means a new cell. When this rate drops below 80%, the current battery is considered unusable for an EV and must be replaced (Schlasza et al., 2014; Omar, 2012). SOH detection is usually due to either battery capacity decrease or increased internal resistance. The decrease in capacity and power decrease is not due to a single reason, but is due to various processes on positive or negative electrodes and also and positive or negative electrodes' interactions (Ekici, 2019).

3.2.3. SOT

The physicochemical properties of the battery are often related to the powerful function of temperature. Temperature changes can significantly affect battery performance, life and reliability (Khaligh and Li, 2010). As the temperature changes, the chemical composition and internal reactions vary at different rates. For example, when the ambient temperature is low, chemical reactions are in a latergic (sleep state) state. This causes capacity losses and high internal resistance. On the other hand, high temperatures, where chemical reactions accelerate, allow the battery to discharge faster (Ekici, 2019). An appropriate operating temperature of each cell is a prerequisite for a healthy battery system. Because current, voltage, SOC and

SOH are all greatly affected by battery temperature (Jossen et al., 1999; Kaiser, 2007). Moreover, high temperature build-up and temperature rise in a cell during charging and discharging can affect the reliability and life of the cell, and may even cause serious safety hazards such as thermal leakage, ie exacerbation (Lin et al., 2011; Man, 2012). Battery temperatures will increase in applications that require high power. Therefore, there is a need for thermal management for batteries (Ekici, 2019).

3.3. Battery Cell Balancing

One of the main tasks of BMS is the equalization of the battery cells. The system, which ensures that the cell voltages are equal when the cells in the battery pack are fully discharged or fully charged, is called battery balancing. If at least one cell in the battery pack differs from other cells in terms of voltage value, it cannot be mentioned that battery balancing has been done. In this case, the battery pack will continue to work with cells with unbalanced voltages. The cell or cells with the least voltage value are determined by the cells connected in series within the battery systems. When the battery pack cannot be properly balanced, the battery capacity may be used less, resulting in range problems. The cell that has the highest capacity from the cells that are imbalance during charging will reach the maximum fullness rate very quickly. In this case, cells with less voltage levels will not be charged to full capacity and will be exhausted earlier (Ekici, 2019). In this case, battery balancing should be designed to keep the cell with the highest voltage level constant and allow the cell with the lowest voltage level to charge. In the battery balancing done in this way, the cell with less full charge will be prevented from discharging early or the cell with a higher charge rate will be prevented from interrupting the early charge. Cell balancing systems are divided into two as active balancing and passive balancing systems as shown in Figure 3.1.

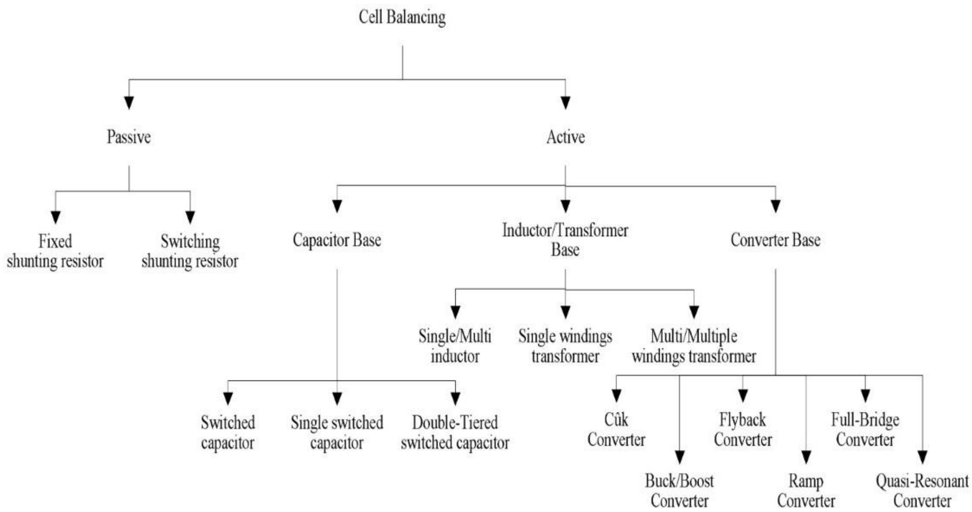

Figure 3.1. Cell balancing topologies (Ci et al., 2016)

3.3.1. Passive Balancing

In order to balance the cells of battery groups, passive balancing method is an easy method.In the passive balancing system, the minimum voltage value in the battery cells is determined and the voltage values of the other battery cells are reduced to this voltage value by consuming energy through the resistors connected in parallel (Rahimi-Eichi et al., 2013). Changes in the voltage values of the battery in the passive balancing system are shown in Figure 3.2. In passive balancing, the energy in the cells with high voltage is spent as heat over the resistances connected in parallel until the voltage level is equalized with the lowest voltage cell and because of the wasting the energy to heat, this method is energy inefficient (Baygüneş, 2019). Passive balancing method is preferred in high Ah value battery packs, where the importance of energy recovery is secondary, due to low cost and easy applicability. It is applied by paying attention to thermal design especially in electric/hybrid electric vehicle applications.

The biggest advantages of these systems are low cost, easy application and a relatively small footprint on the circuit. As can be seen from the figure 3.2, one of the biggest disadvantages is that the capacity used when the occupancy rate of the cells is reduced to a level for the lowest cell decreases significantly.

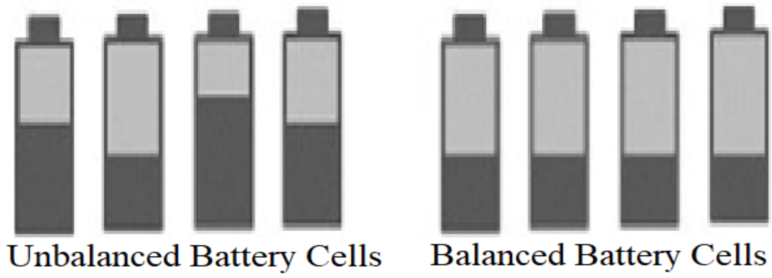

Figure 3.2. Passive balancing (Akgündoğdu et al., 2017)

3.3.1.1. Fixed Shunting Resistor

In this balancing system shown in Figure 3.3 (Kutkut and Divan, 1996), the resistances are constantly active in the case of filling and discharging. It is the simplest method in battery balancing. It provides great convenience in terms of application and cost. It is a very inefficient method due to some of the energy is wasted as heat through the resistor (Savrun et al., 2019).

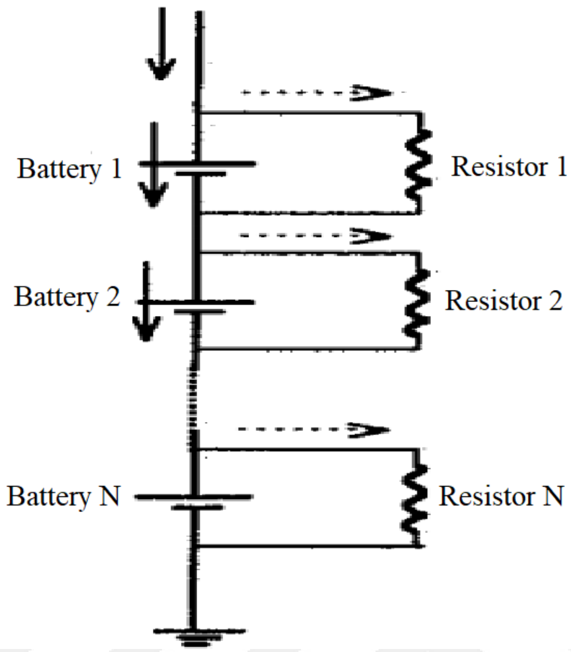

Figure 3.3. Fixed shunting resistor scheme (Kutkut and Divan, 1996)

3.3.1.2. Switching Shunting Resistor

In this balancing method in Figure 3.4 (Daowd et al., 2011), cells are realized by spending excess energy on the resistor by activating the switching element until the cell voltages of a control circuit are equalized. It is the method that is popular in literature. It is used only during the filling of the batteries. It prevents overcharge and protects the batteries (Daowd et al., 2011).

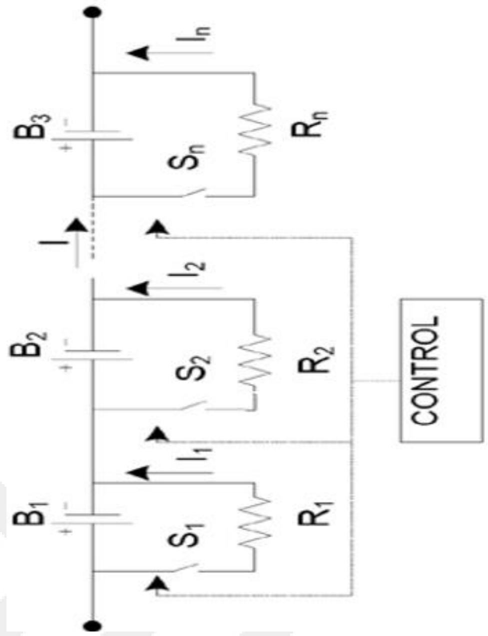

Figure 3.4. Switching shunting resistor scheme (Daowd et al., 2011)

3.3.2. Active Balancing

Another method used for balancing battery cells is active balancing method. The AcBC takes into account the voltage levels of the battery cells and balances them at an average voltage level by transferring energy. For this reason, energy consumed as heat in passive balancing is transferred to other battery cells in active balancing and a more efficient balancing is made (Akgündoğdu et al., 2017). The change in battery voltage levels in active balancing is shown in Figure 3.5 (Akgündoğdu et al., 2017). In applications such as EVs, generally active balancing is a suitable solution to increase vehicle range. In this thesis, AcBS is chosen instead of passive balancing system because of energy efficiency and fast balancing time.

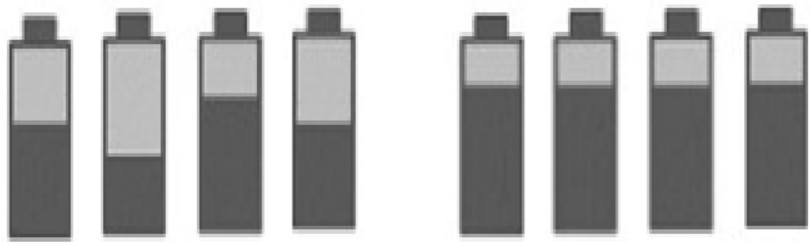

Figure 3.5. Active balancing (Akgündoğdu et al., 2017)

In active balancing methods, elements that can store energy (inductance, capacitor), switching elements which are used in dc-dc converters or power converters can be used. First of all, it is necessary to get to know these basic elements used in active balancing.

3.3.2.1. Elements used in Active Balancing

Elements used in AcBSs can be listed as follows;

*Inductor

* Capacitor

*SuperCapacitor

* Diode

*MOSFET

*IGBT

3.3.2.1.(1). Inductor

The circuit element obtained by winding the insulated conductive wires side by side and on top of each other on a durable insulator called core is called inductor. It is denoted by the letter L. Its unit is Henry (H). Parts of various sizes on which the coils are wound are called mandrel. The fixed or moving part in the mandrel is called a core. Inductors can be made without using mandrel and core are also available.

Such inductors are defined as air core coils. Each winding of the inductor wire is called spir. In Figure 3.6, the inductor and the basic parts used in the inductor are shown (Tarlak, 2018).

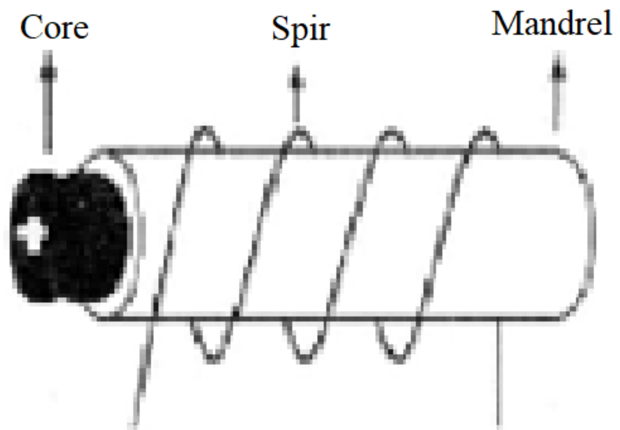

Figure 3.6. Inductor structure (Tarlak, 2018)

While the coils show only as much difficulty as the resistance of the wire in direct current, in the Alternative current also increases depending on the frequency at which the constant value is called inductance. The coil is resistant to DC current at the first moment. Therefore, when DC current is applied to the coil, the coil is the insulator at the first moment and then the conductor. When the AC current is applied to the coil, it shows a resistance because the direction of the current is constantly changing. In short, the coils show little difficulty (ease) to DC current, difficulty to AC current; that is, passing direct current and resistance to alternating current (Anonymous13).

3.3.2.1.(2). Capacitor

The circuit element, which is obtained by placing an insulating material called di-electricity between two conductive boards and capable of storing electrical energy, is called a capacitor. It is denoted by the letter C and its unit is farad (F). The basic structure of the capacitor is shown in Figure 3.7. In DC operation, the capacitor starts charging to the source voltage at the first operation of the circuit. Temporary and gradually decreasing capacitor current flows through the capacitor until the maximum charge process takes place. This current stops when the capacitor is charged with the source voltage (Tarlak, 2018).

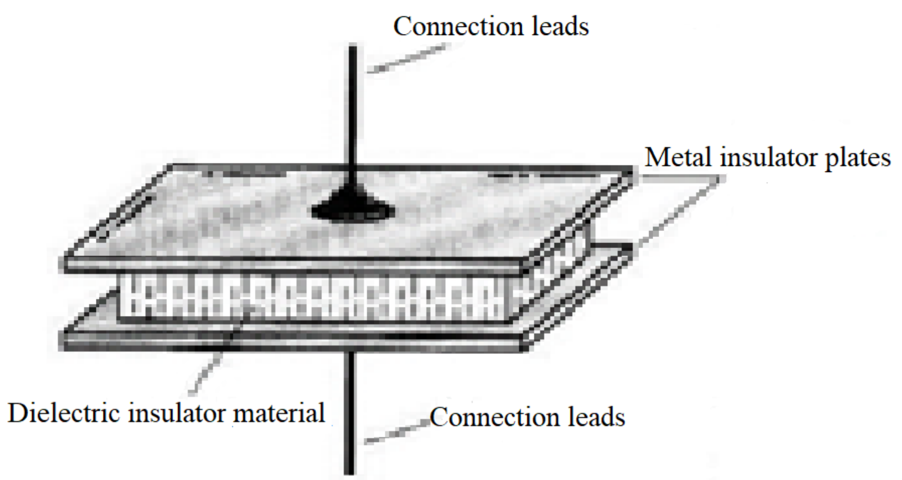

Figure 3.7. Capacitor structure (Tarlak, 2018)

Capacitor types can be listed as paper capacitors, film capacitor, Electrolytic Capacitor, Mica Capacitor, Non-Polarized Capacitor, Ceramic Capacitor (Anonymous14).

3.3.2.1.(3). Supercapacitors

In the energy storage units, supercapacitors, one of the latest products obtained with the development of technology, became the most suitable energy storage unit for EVs. However, it is not yet preferred due to its high cost. Therefore, studies on reducing the cost continues. Supercapacitor structure is shown in Figure 3.8 (Tarlak, 2018).

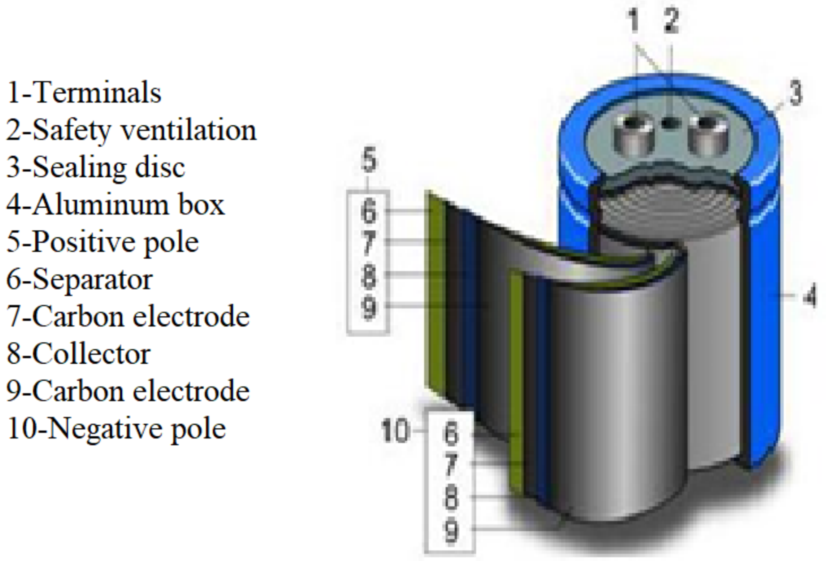

Figure 3.8. Supercapacitor structure (Tarlak, 2018)

Supercapacitors can be charged and discharged 20 times more than electrolytic capacitors, and although there are more than 1000 charge-discharges, their performance does not decrease. It extends the lifetime of the battery system it operates in parallel, and prevents rapid charge/discharge of the battery group due to the energy required to return to the energy storage unit during braking or the high power demand required for sudden acceleration (Tarlak, 2018). There are many studies in the literature on cell balancing topologies using supercapacitors (Maneesut and Supatti, 2017; Yang, 2019; Qu et al., 2013; Jiang et al., 2014; Moore and Schneider, 2001; Barrade, 2002; Li et al., 2018; Pai et al., 2014).

3.3.2.1.(4). Diode

Diode is a semiconductor device that passes current only in one direction. It allows current to flow easily in one direction, but severely restricts current from flowing in the opposite direction. Diode is used in high power applications.The disadvantage is that switching speeds are low. Figure 3.9 shows the Diode icon and the input and output. In order for the current to pass, the voltage must reach a certain threshold. This voltage value of the diode is shown as V_d (Trigger voltage). In DC voltage, it continues to operate in the transmission even if the trigger voltage is cut after the diode is conductive, but the transmission stops when the trigger voltage is cut off in AC voltage (Tarlak, 2018).

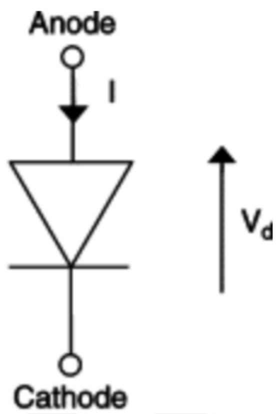

Figure 3.9. Diode symbol (Grout, 2008)

While the transmission stops, the resistance between the anode and cathode is very high and no current flows through the diode. When triggering voltage is applied to the gate end, the resistance between the anode and cathode drops very much and the current starts to pass through the diode.

3.3.2.1.(5). MOSFET

MOSFET (Metal Oxide Semiconductor Field Effect Transistor) is a preferred semiconductor switching element in high frequency, low and medium power applications. A MOSFET, which is not in transmission and has positive voltage at the ends, become transmission mode with the application of voltage to the trigger gate, and stops the transmission after the gate voltage is cut off (Tarlak, 2018). The MOSFET symbol is given in Figure 3.10.

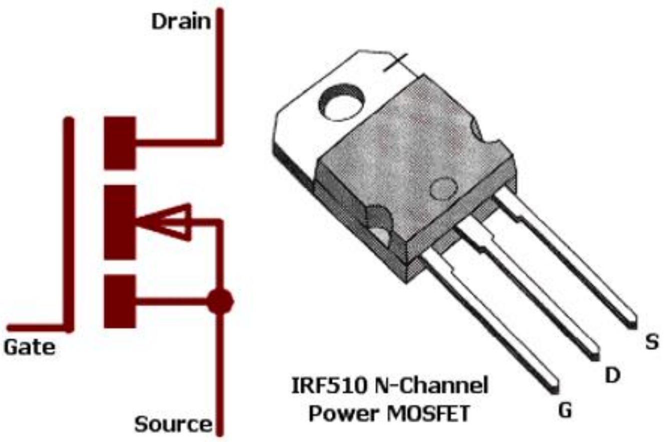

Figure 3.10. Mosfet symbol

3.3.2.1.(6). IGBT

IGBT (Isolated Gate Bipolar Transistors) is a semiconductor switching element used in high voltage, high current and low switching frequencies. Transmission losses are lower than MOSFET (Tarlak, 2018). IGBT symbol is given in Figure 3.11.

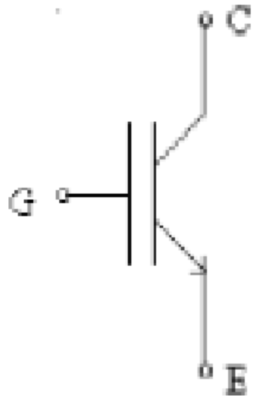

Figure 3.11. IGBT symbol

3.3.2.2. DC-DC Converter Topologies Used in Active Balancing

Although there are often DC power generating power supplies in today's energy systems, the voltage values provided by these resources are not sufficient in some structures. DC-DC Converters are used to convert the unregulated DC input into a controlled DC output at a desired voltage level. DC-DC Converters offer a method of generating multiple controlled voltages from a single battery voltage. DC-DC converters can be insulated and uninsulated types depending on the use of Transformers. It can operate in continuous and discontinuous working modes as a working mode. Examples of non-insulated types are buck, boost, buck-boost and cuk converters. The design of non-insulated types is much easier than transformer connected types, but the most important disadvantage is that there is no isolation between input and output. Flyback, forward, full bridge, half bridge and push-pull converters are the types of the isolated (transformer based) dc dc converters. The most important feature of isolated-transformer types is to provide isolation with a transformer between the input and output, and also more than one output can be obtained (Tarlak, 2018). This section continues by explaining the some of types and properties of dc-dc converters which are used in cell balancing. However, various cell balancing topologies based on the dc-dc converters/elements are given in detail in section 4.

3.3.2.2.(1). Buck-Boost Converter

As a converter that can be used in two ways between DC-DC converters, the basic logic of buck / boost converters, like other converters, is based on switched power supplies. There is one fully controlled switching element on the circuit and the value of the voltage at the output of the circuit is controlled according to the duty cycle value of this element. The basic structure of buck / boost converters is given in figure 3.19. The circuit consists of a voltage source, a switching element, coil, diode, capacitor and a parallel load. Buck / boost converters are a reversing DC-DC converter, which converts the alternation of the input voltage to reverse polarity. While the positive end is at the top, the polarity of the voltage has changed by passing to the bottom at the output. The switching element in the circuit can be switched with the help of a simple driver circuit (Anonymous15). The control diagram of the circuit is the same as the buck converter and the boost converter (buck-boost converter is controlled by generating PWM signal). Buck-boost converter based topologies are used for cell balancing in literature (Zeyuan et al., 2016). When designing a boost converter, D coefficient value, capacitor and inductor values are found by equation 3.7-3.9.

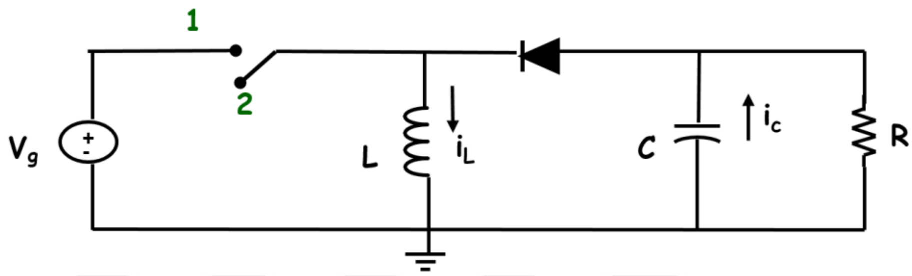

Figure 3.12. Buck-Boost converter

$$D = \frac{Vo}{Vo - Vg} \tag{3.7}$$

$$\Delta V_c = -\frac{Vo}{\mathrm{RC}}.DT_s \tag{3.8}$$

$$\Delta I_L = \frac{Vg}{L}.DT_s \tag{3.9}$$

Buck-Boost converter operates in two modes depending on whether the switch is on and off. When switch is in position 1 (on state), inductor is supplied by input voltage, accumulating energy in inductor, and the output load is supplied by the capacitor (See fig. 3.20). Diode is reverse biased so no current passes through the diode. When switch is in position 2 (off state), energy is transferred from inductor to load and capacitor (See fig. 3.21).

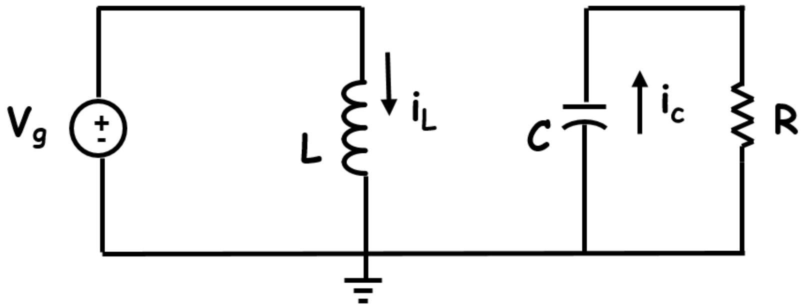

Figure 3.13. Buck-Boost converter (On state)

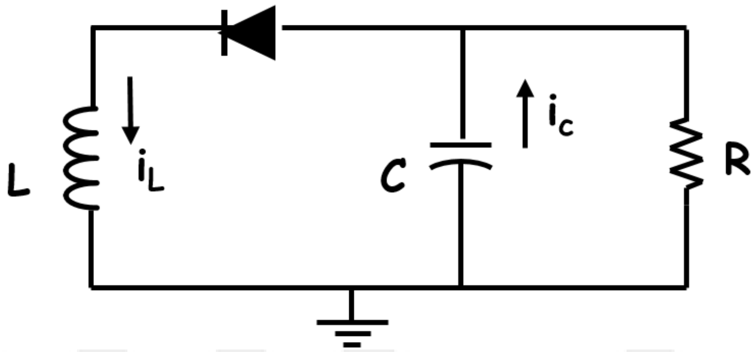

Figure 3.14. Buck-Boost converter (Off state)

There are studies in the literature on cell balancing using a buck-boost converter (Shubiao et al., 2017; Karabeyoğlu et al., 2019; Ji et al., 2016).

3.3.2.2.(2). Cuk Converter

Cuk converters are structures that convert a DC voltage into a different amplitude DC voltage. Cuk converters mainly consist of two inductors and capacitors, one diode and a switching element. The circuit topology of cuk converter is basically given in Figure 3.22. A cuk converter circuit can be obtained by successively connecting the buck converter and boost converter. The polarity of the output voltage is inversely relative to the input voltage, as is the case with buck converter-boost converters. In cuk converter, a capacitor is used as an energy storage element (Anonymous16). Cuk converter based topologies are used for cell balancing in literature (Moghaddam and Van den Bossche, 2019; Yuang-Shung et al., 2005).

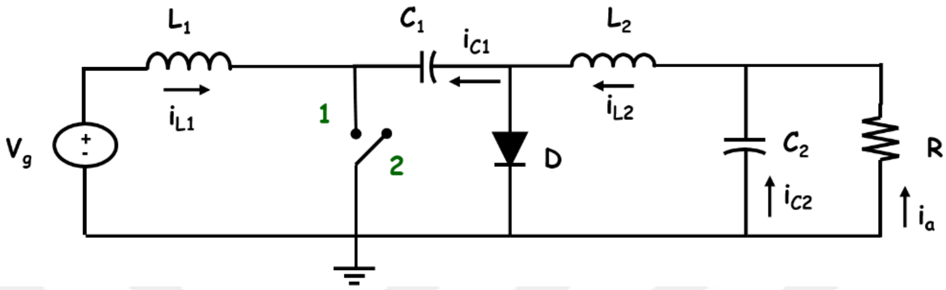

Figure 3.15. Cuk converter

Cuk converter operates in two modes depending on whether the switch is on and off. When switch is in position 1 (on state), current through the inductor L_1 rises, energy is stored in inductor L_1 and the voltage of capacitor C_1 reverse biases the diode and turns it off (See fig 3.23). When switch is in position 2 (off state), the capacitor C_1 is charged by input voltage and the energy stored in the inductor L_2 is transferred to the load (See fig 3.24).

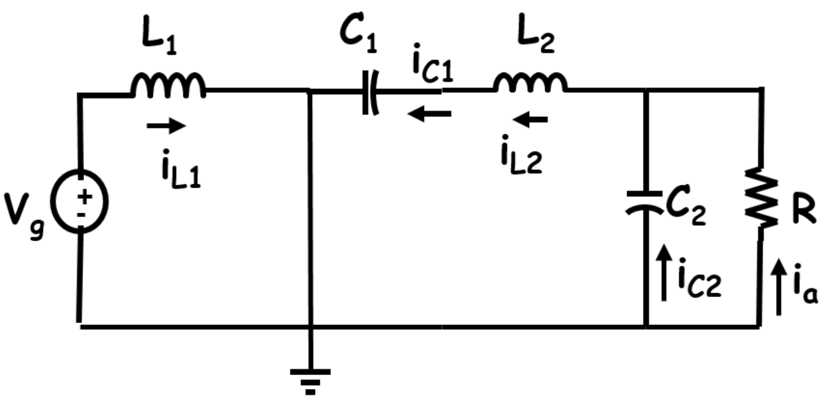

Figure 3.16. Cuk converter (On state)

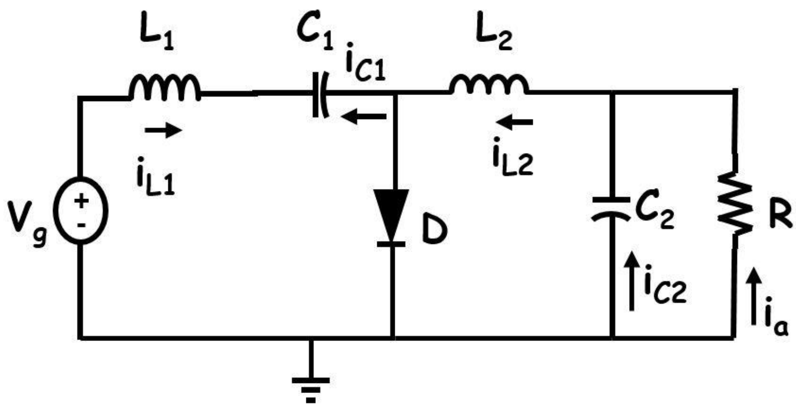

Figure 3.17. Cuk converter (Off state)

3.3.2.2.(3). Flyback Converter

Flyback converters are widely used in switched power supplies because of their simplicity of installation, low cost, multiple outputs electrically isolated from the input and each other, high output voltages, and high efficiency (Ürgün et al., 2009). The basis of flyback converters is based on buck-boost converters. Flyback converters are an insulated form of buck-boost converters. A basic flyback converter consists of a switching element, a transformer, a diode and a capacitor. Flyback circuits can be found in many types due to their structure. These types include structures such as two-switch flyback circuit, RC reset flyback circuit or bidirectional flyback circuit. At first in this thesis, the flyback circuit is explained with its simplest structure. The structure of flyback converter is given in figure 3.25. In addition, the flyback converter has a parallel magnetization inductance that appears on the left side of the transformer as follows. This inductance converter is considered parallel to the transformer in the circuit analysis. Due to the use of transformers in flyback converters, there are restrictions in the circuit, which limits the load on the output of the converter. For this reason, flyback converters are generally used in applications where the output voltage should be high but do not require high power. In buck-boost converters, the polarization of the load voltage in the opposite direction compared to the input voltage is eliminated in the flyback converters. Input voltage and load voltage are polarized in the same direction in flyback converters. The main current at the transformer input and output in the circuit is also the magnetizing current. Although the transformers work with AC signals, it is possible to operate under the effect of the coil located on the left end of the transformer, although DC is given to the input of the system. When the switching element changes from the transmitting state to the cutting state (since the average voltage of the coil is zero in the direct current circuits), the polarity of the voltage at the ends of the coil changes and the direct voltage acts instantly as an alternative voltage, allowing the transformer to operate (Anonymous17). Flyback converter based topologies are used for cell balancing in literature (XueZhe et al., 2009; Farzan Moghaddam et al., 2019; Stefanov et al., 2018; Tian et al., 2018; Pagliosa et al., 2019).

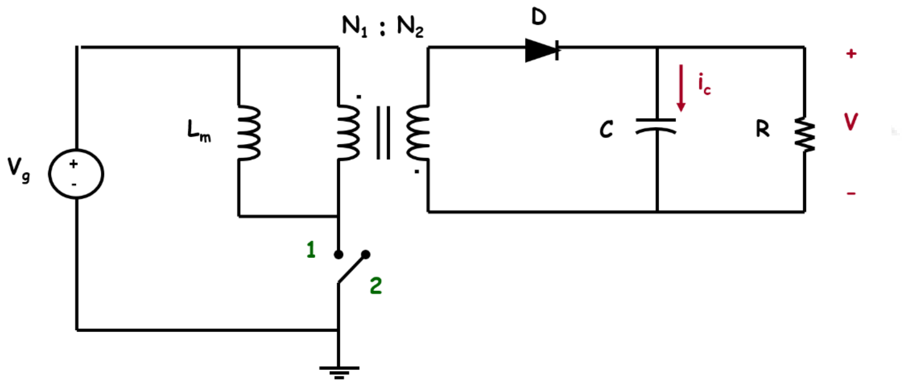

Figure 3.18. Flyback converter

Flyback converter operates in two modes depending on whether the switch is on and off. When switch is in position 1 (on state), the primary of the transformer is directly connected to the input voltage source so this results in an increase of magnetic flux in the transformer. The voltage across the secondary winding is negative, so the diode is reverse-biased. Output load is supplied by the capacitor (See fig. 3.26). When switch is in position 2 (off state), the energy stored in the transformer is transferred to the output of the converter (See fig. 3.27). Design parameters of flyback converter such as D coefficient value (required duty ratio), n (turn ratio of transformer) and the capacitor value can be found by equations 3.10-3.12.

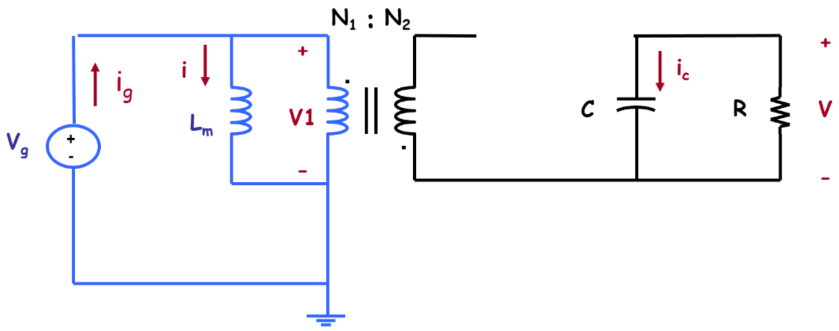

Figure 3.19. Flyback converter (On state)

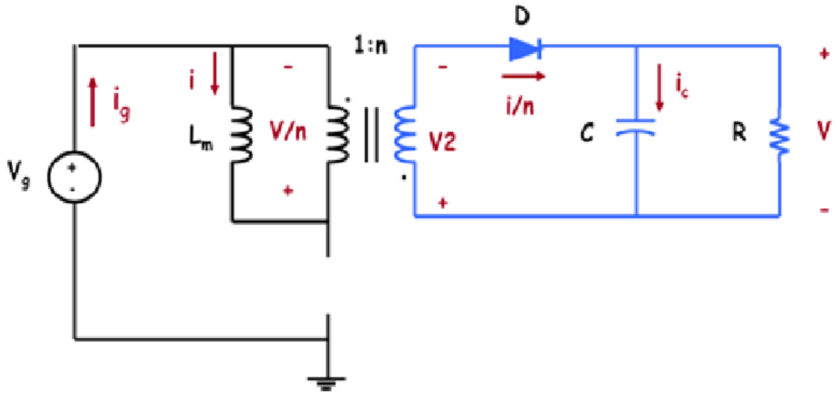

Figure 3.20. Flyback converter (Off state)

$$Vo = \frac{Vg\, n\, D}{(1-D)} \quad (3.10)$$

$$n = \frac{N_2}{N_1} \quad (3.11)$$

$$\Delta V_c = \frac{Vo}{\mathrm{R}C} . DT_s \quad (3.12)$$

3.4. Summary

Firstly, information about BMS and battery parameters are given. Voltage imbalance occurs in a battery cells due to the differences of internal resistance, temperature, self discharge rate, leakage current etc. reduce the usable energy over time. It was mentioned that one of the important task of BMS is to balance the battery cells. The battery management and balancing system is a whole and that the necessary measurements should be taken in order to perform cell balancing. Secondly, a general introduction to the equalization methodologies has been made and why it is mentioned that AcBS is chosen in thesis. Finally, a general introduction to the elements used in active balancing and some of the dc-dc topologies which are used in active balancing has been made.

4. ACTIVE BALANCING TOPOLOGIES AND PROBLEMS IN EHCVS

In this chapter, the difference between active balancing topologies, types of balancing techniques, the advantages disadvantages of these and circuits are presented. In addition, problems in EHCVs are mentioned and information on what can be done to overcome these problems are given.

4.1. Active Balancing Topologies

Active balancing topologies are divided into three main types: Capacitor based, inductor/transformer based and converter based topologies.

4.1.1. Capacitor Based Active Balancing Topologies

In this method, one or more capacitors are connected in parallel to the battery cells. The excess energy from the cell is stored in the capacitor with enabling the necessary switches and the stored energy is transferred to the cell with low energy in order to balance the system. Capacitor-based active balancing topologies can be listed as switched capacitor, single switch capacitor, double-tired switch capacitor and modularized switched capacitor.

4.1.1.1. Switched Capacitor

The related AcBS consists of capacitors, batteries and switches. The switched capacitor method is shown in Figure 4.1. In this method, charge transfer occurs between neighbor-cells from high voltage cell to low voltage cell. Balancing process equalizes the cell voltages regardless of the battery parameters (like SOC). Another nice aspect of switched capacitor circuit is that there is no need for control technique while balancing. Disadvantage of this topology is balancing speed is low (Pascual and Krein, 1997).

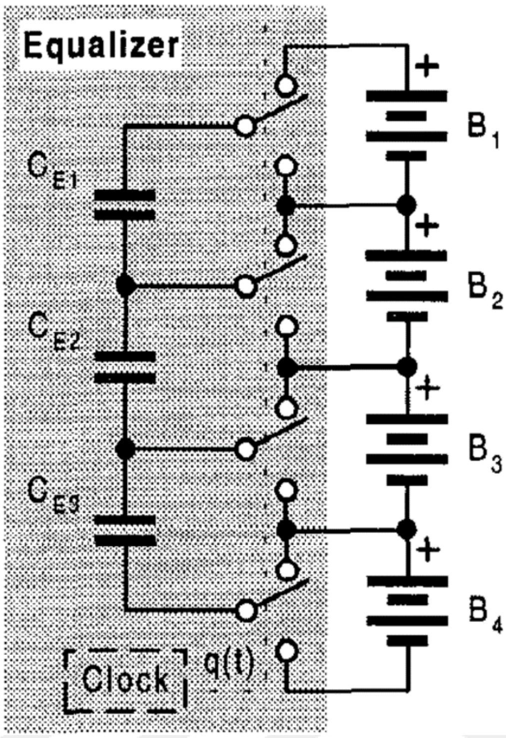

Figure 4.1. SC circuit (Pascual and Krein, 1997)

4.1.1.2. Single Switched Capacitor

The single switch capacitor circuit is similar to the other AcBS which is explained above. The single switched capacitor type AcBC consists of one capacitor, batteries and switches. The related system is shown in Figure 4.2. Since less component is used in this AcBC, it is more cost-efficient than switched capacitor (see in table 4.1). In this method, the cells with the highest and lowest energy cells are determined by controller unit. The necessary switches are enabled to provide charge transfer between these cells in two steps. In the first step, the capacitor is connected in parallel with the highest energy cell by actuating swiches and stores the energy. In the second step, the capacitor is connected in parallel to the cell with the lowest energy by enabling necessary switches and transfers the stored energy to the cell (Daowd et al., 2013). The disadvantage of SSC is the system has low balancing speed (Omariba et al., 2019).

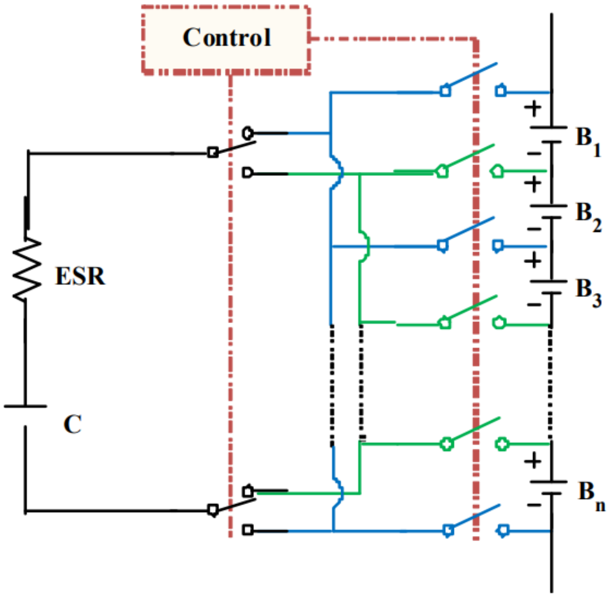

Figure 4.2. SSC circuit (Daowd et al., 2013)

Table 4.1. Comparison of the number of cells and switches of SSC and SC (Daowd et al., 2013)

No. of cells	SC switches (2n)	SSC switches (n+5)
2	4	7
3	6	8
4	8	9
5	10	10
6	12	11
8	16	13
16	32	21

4.1.1.3. Double-Tiered Switched Capacitor

This balancing method is another derivation of SC method. Similarly AcBC of the double-tiered switched capacitor consists of capacitors, batteries and switches. The double-tiered switched capacitor method is shown in figure 4.3. Connecting a new tier help energy transfer between non-neighbor cells which is not the case in SC. Working principle is similar to other capacitive-based balancing topologies. The excessive energy of cell is transferred to the capacitor and that energy is transferred to cell with the low energy. The advantage of this method is balancing speed is better than SC because of having two capacitor tiers for charge transfer (Baughman and Ferdowsi, 2005). The disadvantages of this method are system has high cost, high size and high switch current stress. In addition balancing speed is relatively low (Omariba et al., 2019).

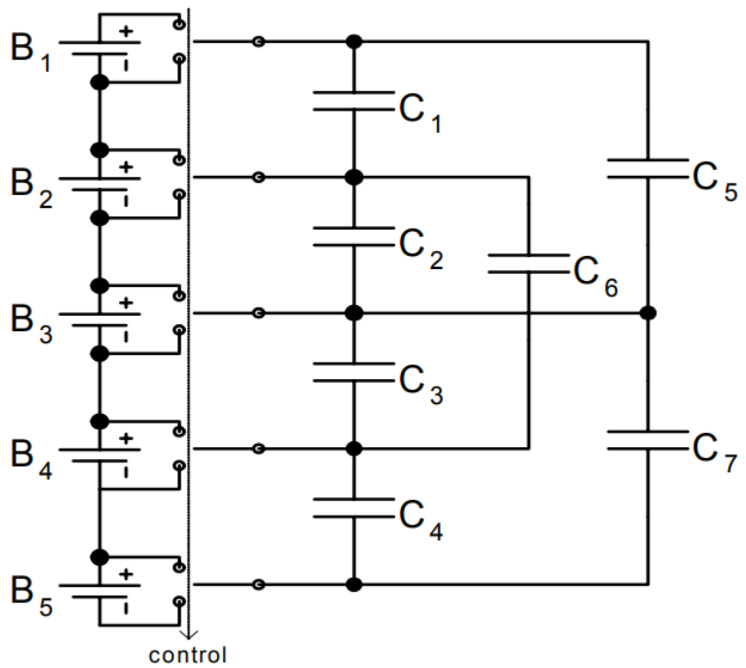

Figure 4.3. DTSC Circuit (Baughman and Ferdowsi, 2005)

4.1.1.4. Modularized Switched Capacitor

MSC is another capacitive-based active balancing method. AcBC of MSC consists of capacitor, batteries and switches. The battery pack is divided into modules. As seen in figure 4.4, there is a separate balancing circuit in each module. The aim of this circuit is to balance the cells in its own module. There is another balancing circuit which perform on module level. Purpose of this circuit is to balance the upper module and the lower module with each other with the help of the high voltage capacitor (Capacitor 7). Combining the two circuits in one system reduces the balancing time because of the working principle. The drawback of this method is the high number of capacitor and high number of switches (Park et al., 2009).

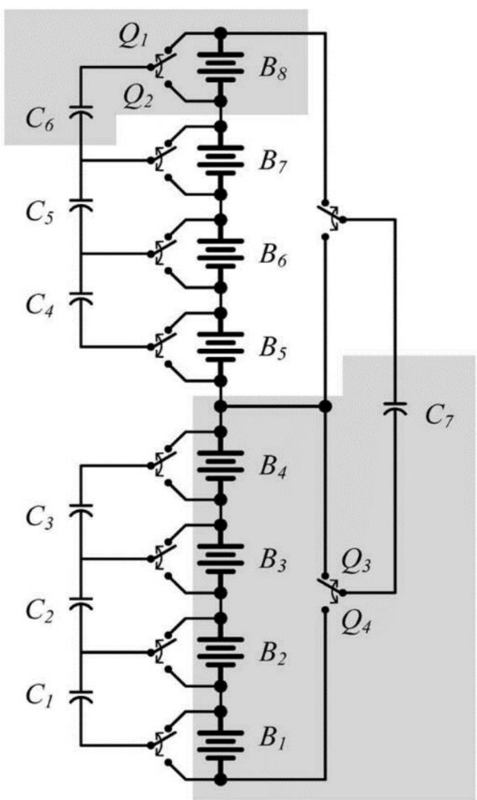

Figure 4.4. MSC circuit (Park et al., 2009)

4.1.2. Inductor/Transformer-Based Active Balancing Topologies

In this method, energy is transferred between the cells by using inductors or transformers to balance the system. Unlike capacitive-based topologies, charge transfer can be perfomed from cells with low voltage to cells with higher voltage. This method has a fast balancing time compared to capacitor based methods (Caspar et al., 2018). Inductor/Transformer-based active balancing topologies can be listed as single/multi inductor, single winding transformer and multi/multiple windings transformer.

4.1.2.1. Single Inductor

The single inductor circuit is similar to the SSC circuit. The main difference between the single inductor and the SSC is that the single inductor method uses an inductor for charge transfer while the SSC method uses a capacitor to transfer charges. The single inductor method is shown in Figure 4.5. The working principle of this AcBC is divived into two steps. Voltages of all cells are monitored and two cells are selected by the controller unit. By actuating the necessary switches the charge transfer occurs between two selected cells. In the first step, some of the energy in the high-voltage cell is transferred to the inductor for storage by enabling the necessary switches. In the second step, the stored energy is transferred to the low voltage cell by activating the necessary switches (Park at al., 2007). The disadvantages of this method are slow balancing speed, high complexity and big size (Omariba et al., 2019).

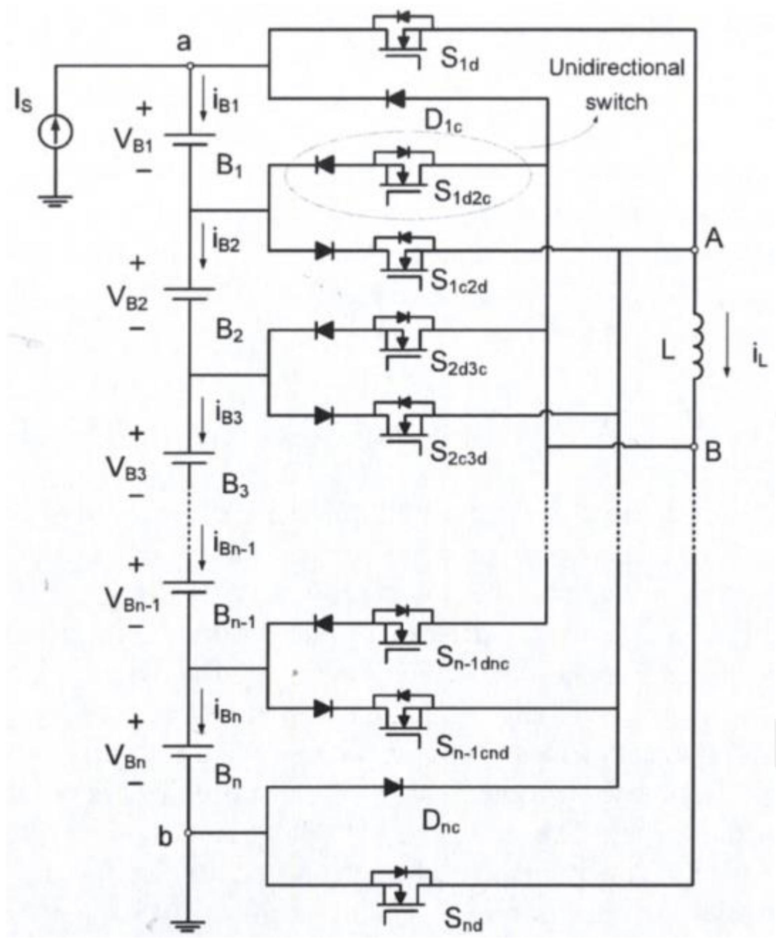

Figure 4.5. Single inductor circuit (Park et al., 2007)

4.1.2.2. Multi-Inductor

Multi-inductor circuit is similar to the single inductor circuit. The main difference between two of these circuits is the number of inductors used in the balancing process. To balance n number of battery cells, n-1 number of inductors are used (see Figure 4.6). In the circuit, transistors are used as switches. Energy is transferred between only neighbor cells. Firstly, the transistor, connected in parallel to the high-voltage cell, is actuated by the PWM signal and energy is stored in the inductor. Then, the transistor adjacent to the switched transistor is triggered by the

PWM signal while first transistor turned off so that it can energize the low voltage cell. The drawback of this method is direct charge transfer cannot be performed between nonneighbor cells so unnecessary steps are occurred if there is an imbalance between battery cell V1 and battery cell V3 (Phung et al., 2011).

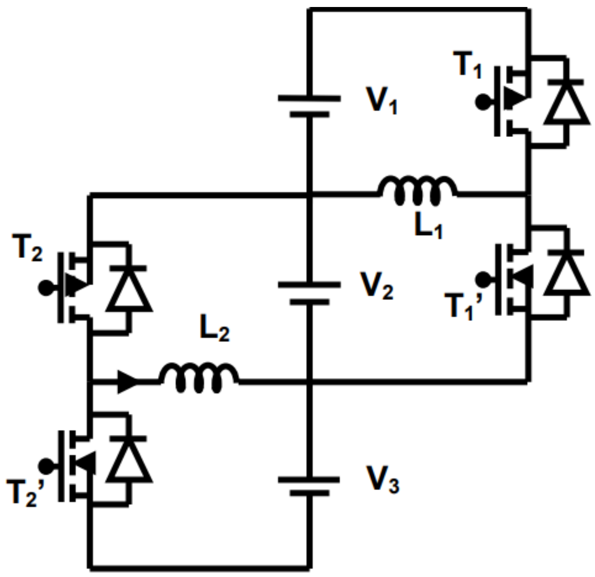

Figure 4.6. Multi-inductor circuit (Omariba et al., 2019)

4.1.2.3. Single winding transformer

The single winding transformer circuits are based on battery cells which have serial connection with each other and flyback converter (see figure 4.7). In this topology, 2 different methods are generally used for cell balancing. The first method is called pack to cell technique. The purpose of this method is to perform charge transfer from the battery module to cell with the low voltage. Firstly, cell with the lowest voltage is determined. When switch is in transmission, energy is stored in one winding of the transformer. After the switch is disabled, stored energy is transferred to the weakest cell. The Transfer is occurred from module to weak cell(s) by enabling the transformer and necessary switches (Imtiaz et al., 2011). The Second method is called cell to pack technique. The purpose of the second method is to perform charge transfer from cell(s) with high voltage to the battery module. The Balancing process is operated by actuating the transformer and necessary switches (Shin et al., 2010). The disadvantages of this topology are its high cost and high control complexity (Ci et al., 2016).

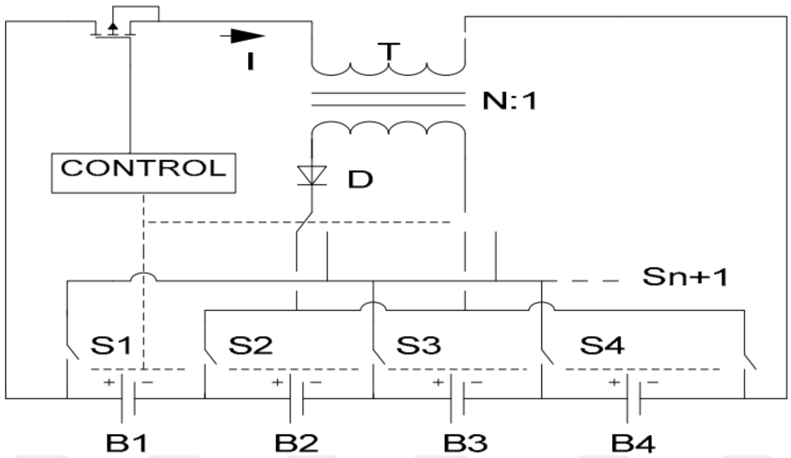

Figure 4.7. Single winding transformer circuit (Cadar et al., 2010)

4.1.2.4. Multi-windings transformer

The circuit of Multi-windings transformer based AcBC is similar to the single winding transformer based AcBC. The main difference of Multi-winding transformer is that the AcBC of the secondary windings are connected with individual battery cells (see figure 4.8). In this method, the balancing process starts when the switch which has a connection with a shared winding is enabled so energy is stored through the primary winding. Then the switch is disabled and the stored energy is delivered to the weak cells through secondary winding by actuating the necessary switches (Bonfiglio et al., 2009). The disadvantages of this topology are its high cost and high control complexity (Ci, 2016).

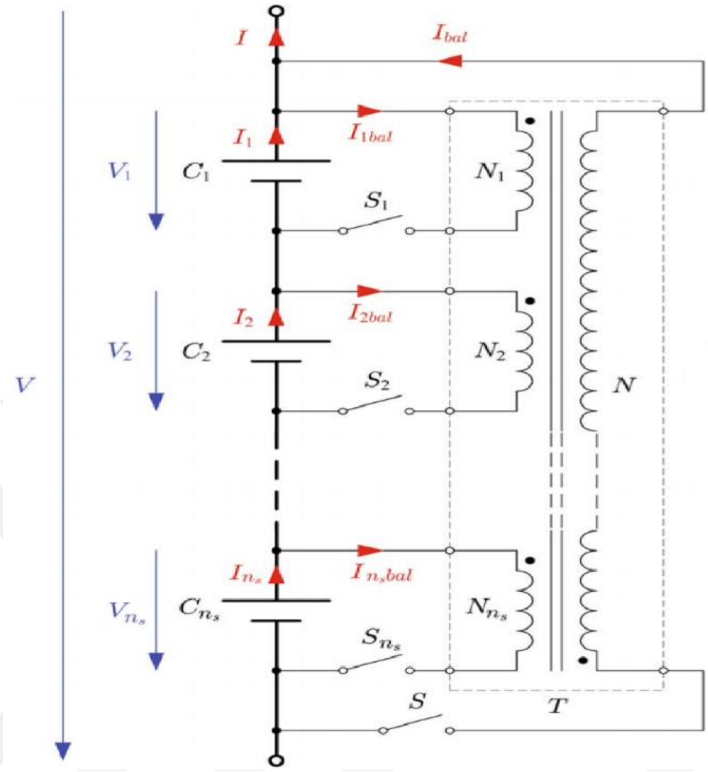

Figure 4.8. Multi-windings transformer circuit (Einhorn et al., 2011)

4.1.3. Converter based topologies

In this method, converters are connected by considering each or a series of connected cells as a group and balancing is performed with converters. Converter-based active balancing topologies can be listed as cuk converter, ramp converter, Full-bridge converter, Quasi-Resonant converter, buck-boost converter and flyback converter. Since the buck-boost converter circuit and the multiple inductor circuit are very similar and the multi-inductor circuit is described in one of the previous section, there is no need to explain the buck-boost converter based active balancing topology in this section.

4.1.3.1. Cuk converter

As explained in the dc-dc converter section (3.3.2.2), cuk converter circuit consists of capacitors and inductors (see fig. 4.9). Difference from capacitive or inductor/transformer based balancing circuits is both of the elements (capacitor/inductor) are used for charge transfer instead of using one element. Important feature of the cuk converter is that the circuit provides bidirectional power for balancing. Cell to cell technique is used for cuk converter based AcBC and working principle is shown in figure 4.10. In this method, energy is stored and shifted from the cell with high voltage to the cell with low voltage (Cell 1 voltage is bigger than cell 2 in figure y). The balancing process starts by sending PWM signal to enable mosfet Q1 so cell 1 start to discharge to the inductor (L1). L1 stored the energy and on the bottom side capacitor discharges to cell 2. L2 also stores energy. When Q1 is off, L1 charges the capacitor with its own stored energy. L2 continues to charge cell 2 and operating process is finished when system is balanced. In short, both of the elements are used to transfer the energy between neighbor cells (Yan et al., 2010). The disadvantages of this circuit are high control complexity, relatively big size and low implementation (Omariba et al., 2019).

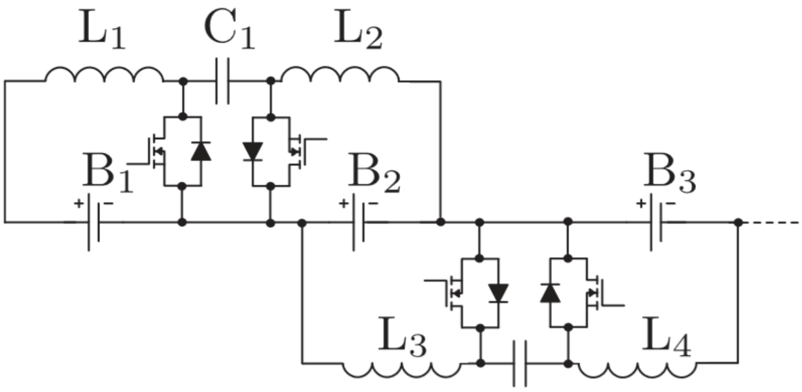

Figure 4.9. Cuk converter circuit (Caspar et al., 2018)

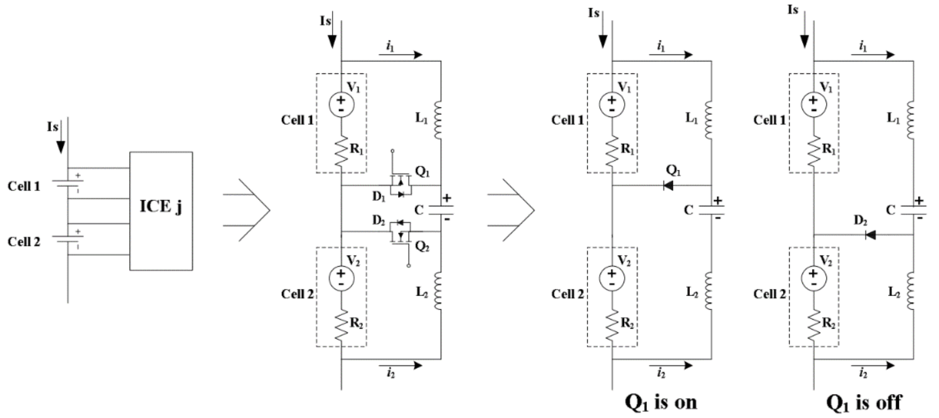

Figure 4.10. Operating principle of cuk converter in balancing process (Yan et al., 2010)

4.1.3.2. Ramp Converter

Ramp converter topology has a similar working principle like multiple windings transformer. AcBC of the balancing topology is shown in figure 4.11. In the balancing system, battery cells are supplied by currents. The energy is transferred from the battery pack to the batteries with low voltage levels. The operating principle of this topology can be summarized in two half cycles. In the first half cycle, odd-numbered cells that have low voltage levels are charged. In the second half cycle, even-numbered weak cells are charged (Tang and Stuart, 2000). The disadvantage of this circuit is complex control.In addition, balancing speed is not fast enough (Daowd et al., 2011). As can be seen from the current graph in Figure 4.12, the current goes from zero to positive peak and peak to zero. Similarly current goes from zero to negative peak and peak to zero. Since the current behaves like that, this balancing topology is called a ramp converter.

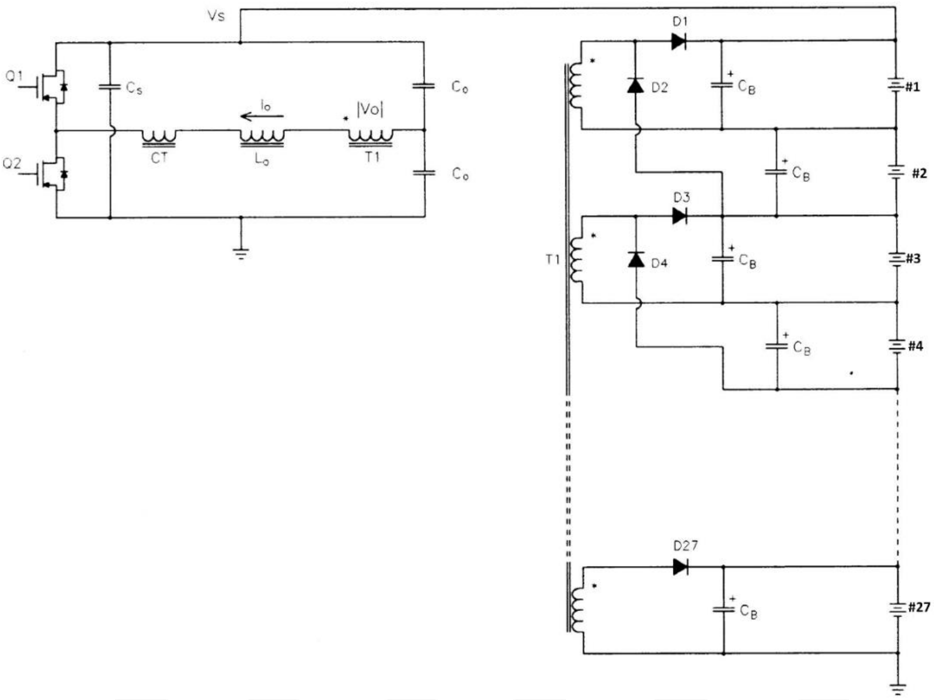

Figure 4.11. Ramp converter circuit (Gotwald et al., 1997)

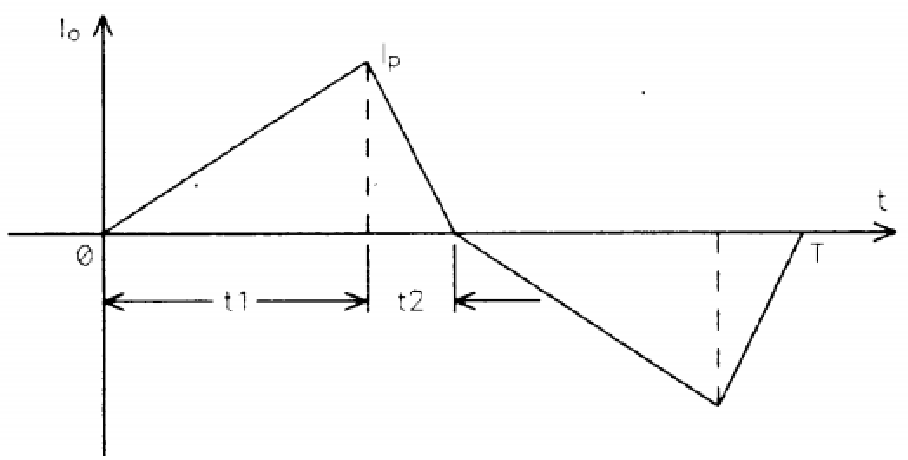

Figure 4.12. Current graph of ramp converter circuit (Gotwald et al., 1997)

4.1.3.3. Full-bridge Converter

This topology acts as a fully controlled energy converter. In this method, pack to cell technique is used. The working principle of the related AcBS depends on the PWM signals which are used for enabling the MOSFETs. Voltages of all cells are monitored by the controller unit. In order to balance the cell voltages, energy is tranferred from whole pack to weak cell. This topology can be used for AC/DC OR DC-DC converter and shown in figure 4.13 (Gallardo-Lozano et al., 2014). The disadvantages of this topology are high cost, complex control and big size (Omariba et al., 2019).

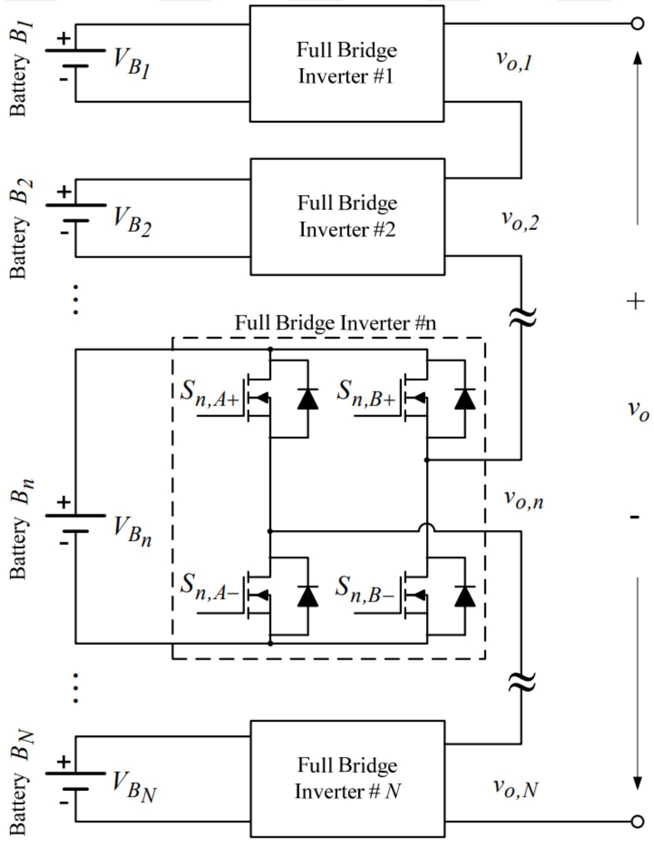

Figure 4.13. Full bridge converter circuit (Young et al., 2013)

4.1.3.4. Quasi-Resonant Converter

The main difference from the full-bridge converter is that this topology uses resonant circuits to transfer charges and actuate switches instead of generating pwm signals by an intelligent control mechanism. In addition cell to cell balancing technique is used and topology is given in figure 4.14. Excessive energy is transferred from cell with high voltage to cell with low voltage. This AcBC achieves the zero current switching function for bi-directional power flow (Daowd et al., 2011). The disadvantages of this topology are expensive, high control complexity and having big sized (Omariba et al., 2019).

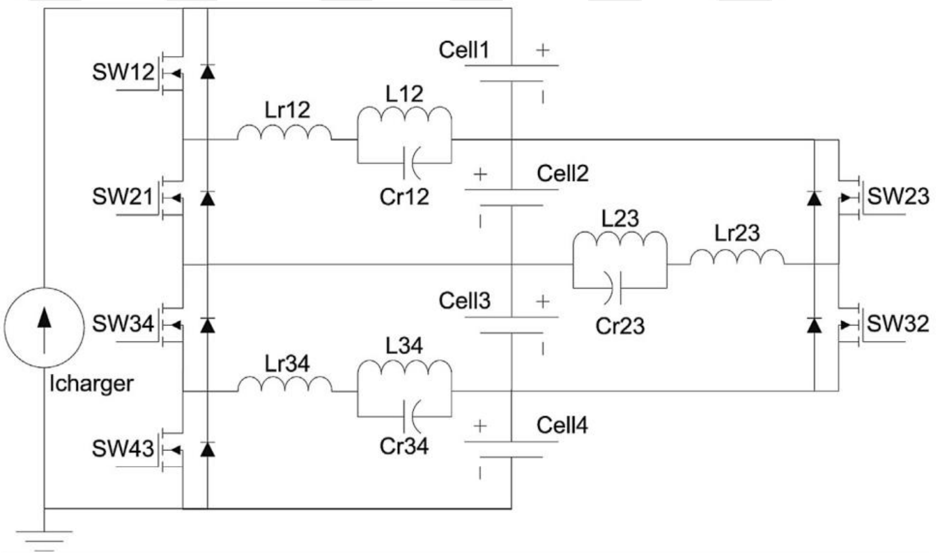

Figure 4.14. Quasi-Resonant converter circuit (Gallardo-Lozano et al., 2014)

4.1.3.5. Flyback Converter

Flyback converters are used for AcBCs and there are two different types of flyback converters. In unidirectional flyback converter topology, charge transfer occurs when the coupled switch is actuated. The excessive energy of the cell with high voltage is transferred to the transformer. When the switch is disabled, stored energy is transferred to the pack from the transformer. In BiFLC topology, energy can be transferred from pack to cell and vice versa. The topology of BiFLCis shown in figure 4.15. Basic working principle of BiFLC is as follows (Lin et al., 2016):

1) Voltages of each cell are monitored by the controller unit and the average cell voltage in the battery pack is determined.
2) When cell voltage (Vbat) is bigger than the average voltage, primary side switch is actuated. Energy is stored in primary magnetizing inductor.
3) When primary switch is disabled, stored energy in inductor is delivered to the Vcapacitor.

In chapter 5, BiFLC's working principle is explained in detail.

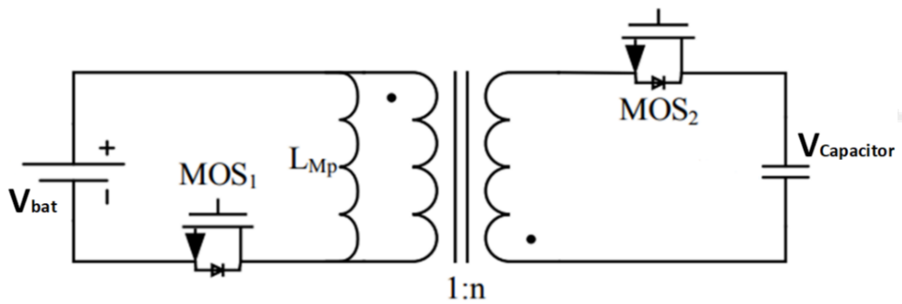

Figure 4.15. BiFLC circuit (Lin et al., 2016)

4.2. Problems in EHCVs

Some of the problems of EHCVs are expensive battery technology, high charging time and lack of the number of charging stations. However, one of the most important problem of EHCV is range problem. In the past, Conventional vehicles traveled about 500-600 kilometers on full tank fuel, while EVs mostly used lead-acid or nickel cadmium, whose range is hard to see 45 kilometers. Today, lithium ion battery type is used for EHCVs because the most important advantage of lithium-ion batteries over other types of rechargeable batteries is high energy density. High capacity battery packs are needed to solve the range problem. Battery cells are connected in parallel or in series or in a combination of both to reach high capacity battery packs. Although this method solves the capacity problem, unbalance occurs both between the packages and between the cells. Battery balancing system has many important benefits. Their capacity decreases as the batteries are charged and discharged. As a result of the unbalanced charge and discharges, the batteries may be failed before they complete their standard lifetime, and quickly become inactive. However, more energy can be drawn from the batteries used with the cellular balancing system and the lifespan of these batteries will be longer (Akgündoğdu et al., 2017). In order to solve the balancing problem in EHCVs, AcBC is needed. In chapter 6, active balancing model and an algorithm are proposed for LBPs which are used in EVs.

5. INTRODUCTION TO THE SYSTEM, CONTROL SCHEME, MODELING OF THE SYSTEM AND SIMULATION RESULTS

5.1. System Description

5.1.1. BiFLC

There exists a very extensive literature on the topic of using bidirectional flyback on active cell balancing. BiFLC is used as dc-dc converter in this thesis because the advantages of the converter such as being easy to modeled (simple structure), low cost and providing bidirectional flow of energy are taken into consideration (Gopalakrishnan and Dharani, 2015). In addition, having other advantages such as easy implemented for large number of cells, ideal for transportation application (EV/HEV application) and good balancing speed (Daowd et al., 2011) makes BiFLC suitable for LBPs. As shown in figure 5.1, BiFLC consists of two inductors and two power switches.

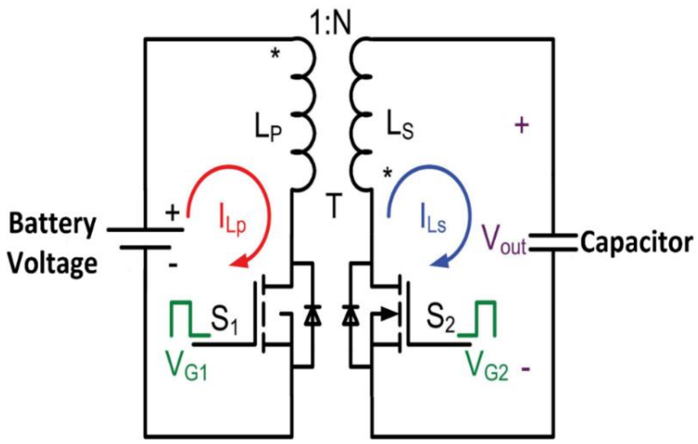

Figure 5.1. The topology of BiFLC

In order to understand the balancing process of one module, ıt is necessary to learn the working principle of BiFLC.

5.1.1.1. Energy transfer process analysis

The battery is connected to the left side of the circuit and a capacitor is connected to the right side of the circuit. In the first stage, the electrical energy is transferred from battery to capacitor. By generating PWM signal, switch 1 is enabled and the energy transfer process is initiated. When switch 1 is open, magnetic energy is accumulated and the inductor on the primary side is magnetized. Then switch 1 is off. With the help of the inductor on the secondary side, the stored energy is transferred to the capacitor through the diode in mosfet 2. In Ideal situation, the magnetic energy of the secondary inductor is totally transformed into electrical energy in the capacitor. In every off-time of switch 1, current passing through secondary inductor can be expressed in equation 5.1. Similary in every off-time of switch 1, output voltage can be expressed in equation 5.2 (Huang et al., 2012).

$$i_{L_s}(t) = i_{L_s}(0).\cos\left(\frac{t}{\sqrt{L_s.C}}\right) - V_{out}(0).\sqrt{\frac{C}{L_s}}\ .\sin\left(\frac{t}{\sqrt{L_s.C}}\right) \qquad (5.1)$$

$$V_{out}(t) = V_{out}(0).\cos\left(\frac{t}{\sqrt{L_s.C}}\right) + i_{L_s}(0).\sqrt{\frac{L_s}{C}}\ .\sin\left(\frac{t}{\sqrt{L_s.C}}\right) \qquad (5.2)$$

LS is the inductance of secondary coupled inductor, C is the capacitance value of capacitor, and iLs(0), Vout(0) are the initial current and voltage for inductor and actuator, respectively. When the current passing through the diode in Mosfet 2 completes the path in the previous cycle, the next cycle begins immediately. The waveforms of first few cycles in energy transfer process are shown in Figure 5.2 (Huang et al., 2012).

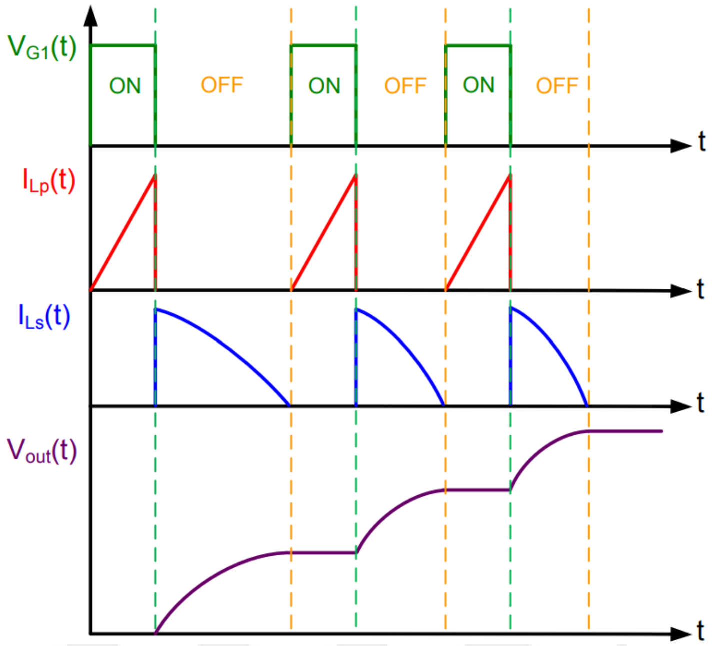

Figure 5.2. Waveforms of BiFLC in the energy transfer process (Huang et al., 2012)

5.1.1.2. Energy Recovery Process Analysis

In order to prolong the life of the battery, it is very important to recover the energy stored in the capacitor. Similar to the energy transfer process, by generating PWM signal, switch 2 is enabled and energy recovery process is initiated. During the process, switch 2 and diode in mosfet 1 perform their tasks. When switch 2 is open, the inductor on the secondary side receives magnetic energy from the capacitor. When switch 2 is closed, it transfers the stored energy to the primary side. The waveforms of first few cycles in energy transfer process are shown in Figure 5.3 (Huang et al., 2012).

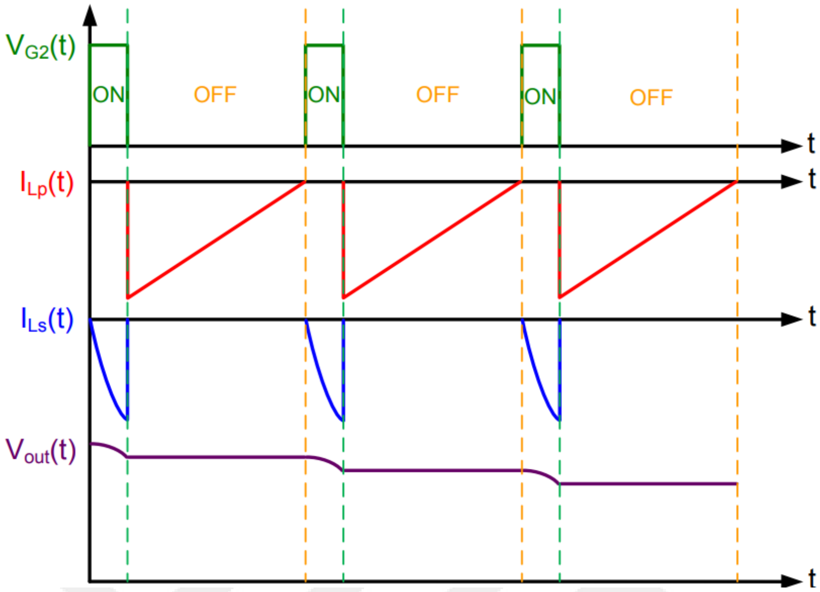

Figure 5.3. Waveforms of BiFLC in the energy recovery process (Huang et al., 2012)

5.1.2. Switch Matrix

The FET switches in a switch matrix are divided into two categories. See Figure 5.4 for a detailed illustration. The switches directly connected to the battery cells are called the “cell switches”. Each cell switch is comprised of two N-FETs that are connected in a common source and common gate manner and is capable of blocking current flow in both directions. The switches directly connected to the DC/DC converter are called the "polarity switches". Each polarity switch is simply an N FET and is capable of blocking current flow in one direction only. Switch Matrix is used to select a target cell for balancing (Anonymous18).

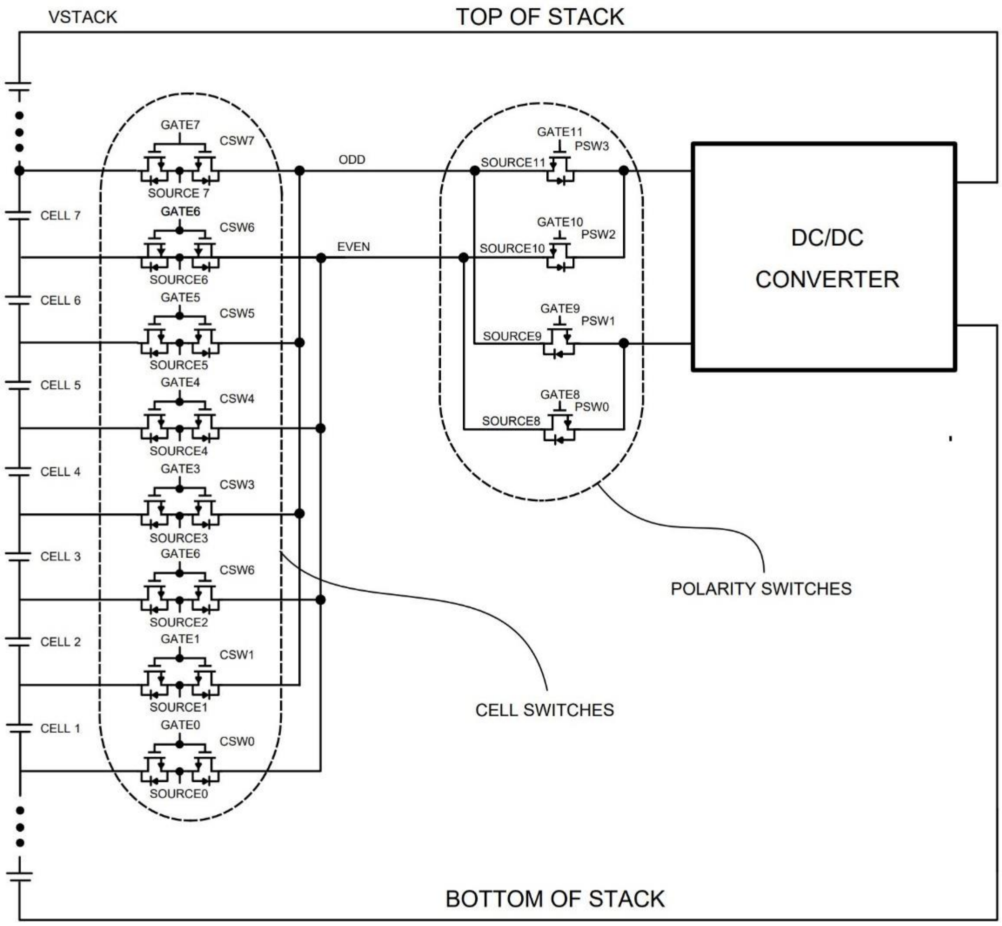

Figure 5.4. Switch matrix (Anonymous18)

5.1.3. Small Scale Active Balancing System (One module)

Before proceeding to charge transfer operation in LBPs, it is necessary to check whether the balancing in one module is working properly. To evaluate the performance of small scale balancing system, the circuit which consists of battery modules and BiDC converters equipped with switch matrix have been modeled by using Matlab/Simulink. The presented model provides a bidirectional power flow to perform charging/discharging operations between source/destination cells. BiDC converter provides the isolation and charge transfer between battery cells and the bus. One module consists of 2 submodules and each submodule consists of 8 series cells. Different methods can be used to obtain the switching signal of dc-dc converters. In this thesis, SIMULINK's PWM generator is used to enable the switches in small scale AcBS.

5.2. Adapting the System to Large-Scale

In this thesis, two studies were investigated in active balancing process while adapting the LBPs. First study is based on active balancing model and two cases are carried out to see the performance of the model. In the second study, a new balancing algorithm is proposed and three cases are examined in SIMULINK by comparing the proposed algorithm with existing algorithm.

5.2.1. Study 1: An Active Balancing System for LBPs Used in EHCVs

In the first study, active equalization circuit is presented for LBP. To test the balancing performance, active equalization topology is simulated by using MATLAB-SIMULINK. Presented model's one module consists of two sub-modules. Each sub-module has eight cells endowed with BiFLC-switch matrix combination. The presented AcBC has a bidirectional power flow feature. In other words, both charging and discharging operation are performed by AcBC. To provide energy transfer, necessary switches must be enabled. Swm give a link between BiFLC-battery cells in each sub-module. BiFLC provides bidirectional charge transfer between battery cells-ctb. SwM's switching structure is divided into two parts. The first part is called cell switches. Source/destination cells are selected by cell switches to start balancing. The second part is called polarity switches. These switches operate with the consideration of polarity of source/destination cells which is shown in figure 5.5.

To evaluate LBP performance easily, current sources are used instead of BiFLC-SwM combination in simulation model. To analyze the performance of two sub-modules, BiFLC-SwM based AcBC is tested in the simulation model. Its accuracy is clarified for two sub-module. However, modeling of large scale has high run time and complexity. In the thesis, current sources are used to test AcBC performance easily. The system explained for LBP in the thesis is shown in figure 5.6. The system consists of eleven modules and each module consist of two sub-module. Each sub-module has eight series-connected cells. The cell nominal voltage is 3.7 volt. Presented topology has 176 series-connected cells. The total voltage of the AcBC is 650 volt. The total capacity of the system is 110 amp-hour.

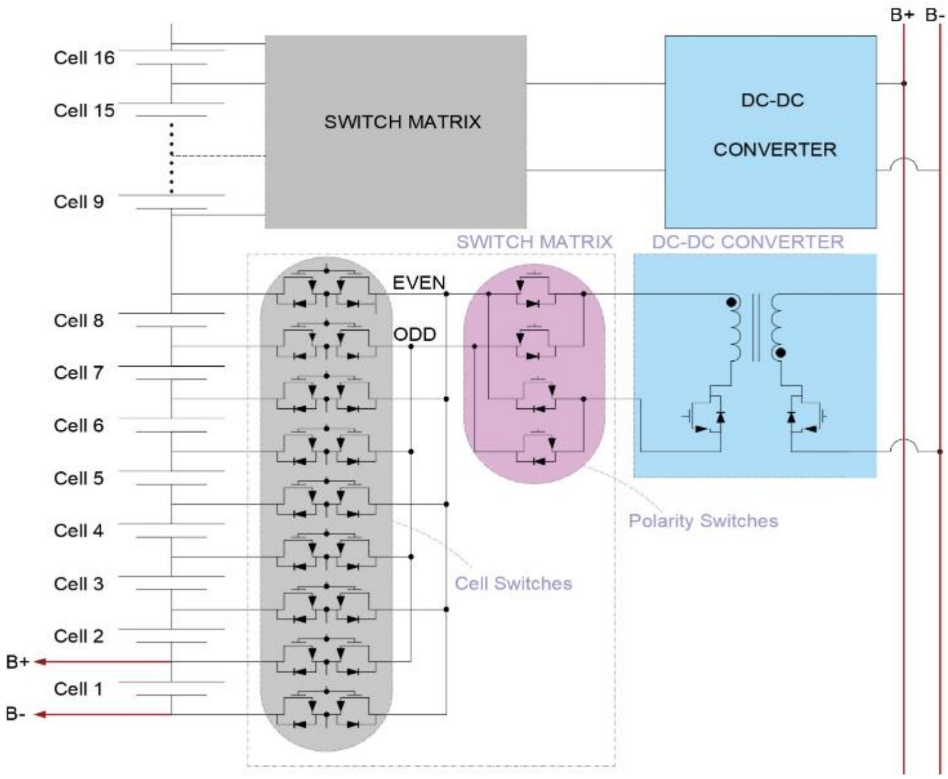

Figure 5.5. The simulation model of the one module with BiFLC (presented model)

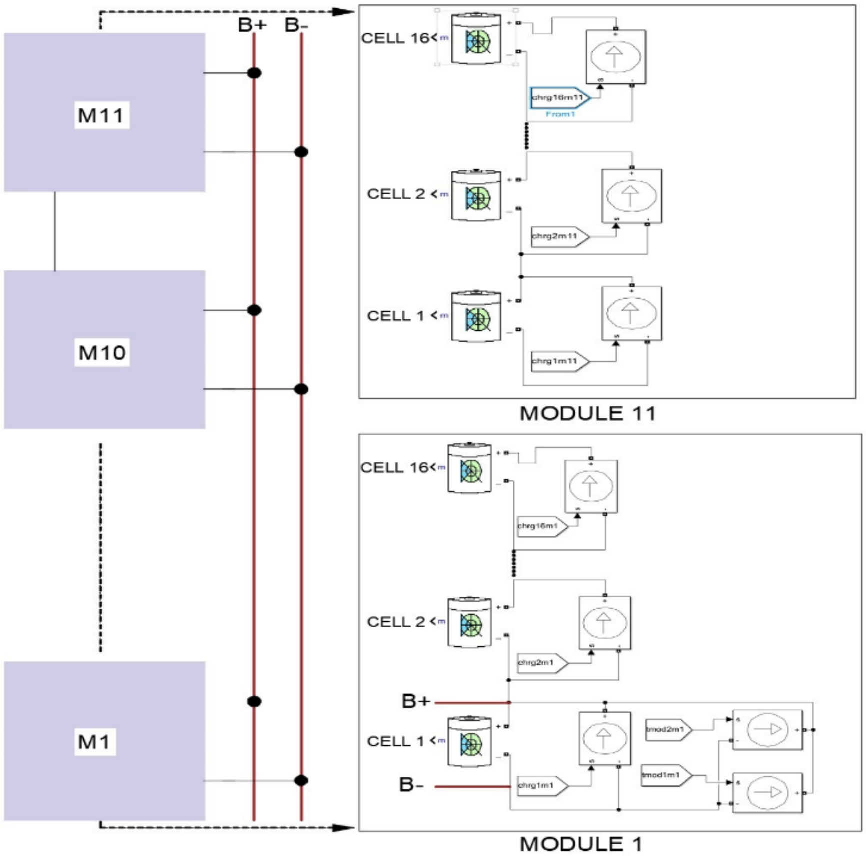

Figure 5.6. The simulation model of AcBS (presented model)

Charge transfer is operated with the use of ctb. The difference of presented topology is, ctb is fed by first cell of first module so a different approach is provided in the thesis. Thus, the necessity of auxiliary circuit or auxiliary battery is eliminated too. In addition, another modeling has been done by selecting multiple cells to feed ctb. System is tested with comparision of two models to see which approach has better balancing time (first cell or multiple cells).

5.2.1.1. Study 1's Control Scheme

Control mechanism of presented AcBC depends on voltage imbalances in battery modules. The 176 cell voltage in the system, which has 11 modules in total, is constantly monitored by controller unit. Controller unit determines one maximum and one minimum cell voltage per sub-module. In total 22 maximum and 22 minimum cells are selected because presented AcBC has 22 sub-module. As shown in equation 5.3, balancing process is initialized by controller unit if the difference between the maximum cell voltage and minimum cell voltage is more than 5mV. Maximum cell voltage is shown as Vmax_mi and minimum cell voltage is shown as Vmin_mi in the equation. Charge/Disharge operation is determined in equation 5.4 with the consideration of the difference between Vmin_mi and average of sub-module voltages (Vavg_mi) and the difference between Vmax_mi and Vavg_mi. Cells with highest voltages are called source cells and cells with lowest voltages are called destination cells. Excessive energy from source cell to destination cell is transferred via ctb.

$$\begin{aligned} &balancing\ starts \quad V_{max\_mi} - V_{min\_mi} > 5mV \\ &balancing\ ends \quad V_{max\_mi} - V_{min\_mi} \leq 5mV \end{aligned} \tag{5.3}$$

$$\begin{aligned} &discharge\ operation \quad V_{max\_mi} - V_{avg\_mi} > V_{avg\_mi} - V_{min\_mi} \\ &charge\ operation \quad V_{max\_mi} - V_{avg\_mi} < V_{avg\_mi} - V_{min\_mi} \end{aligned} \tag{5.4}$$

After deciding the direction of power flow in each module, related current sources are enabled with the consideration of Swm switching algorithm. Related cell number is called n in the module. Working principle of SwM switching algorithm is if the source/destination cell is in the first sub-module, n and n+1 cell switches are actuated. If source/destination cell is in the second sub-module, n+1 and n+2 cell switches are actuated. In this way, a bridge is established between the related cells and ctb with the help of BiFLC. Polarity switches are actuated according to whether the source/destination cell is odd number or even number. If the related cell is odd number, two polarity switches in the middle are enabled. If the related cell is even number, 2 polarity switches on top and bottom are enabled. Controller unit measures the voltages of 176 cells with sampling time of 10ms. Thus current information is taken and location of switches are refreshed every 8 seconds. Basic flowchart of AcBC's balancing algorithm is seen in figure 5.7.

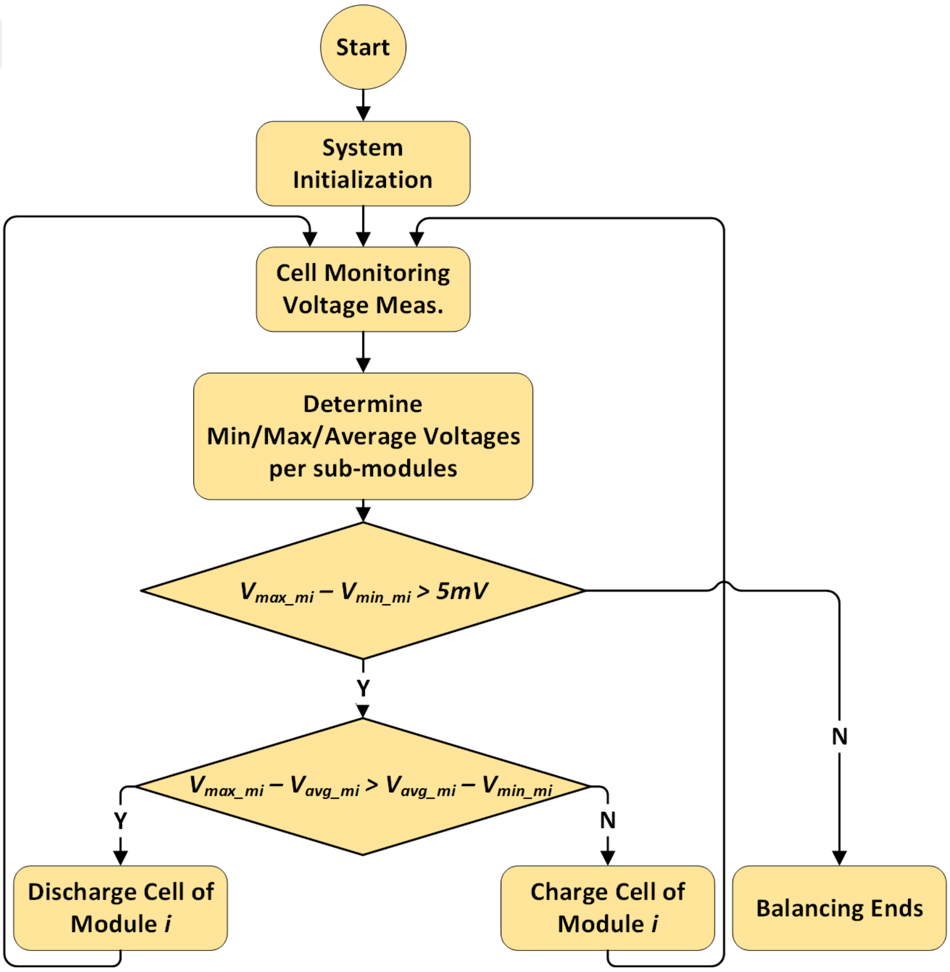

Figure 5.7. The flowchart of AcBS balancing algorithm (presented model)

5.2.1.2. Study 1's Simulation Results

The balancing performance of AcBS that is modeled in the first study is evaluated under 2 case studies using LBP which consists of 11 modules and each module consists of 16 cells. SOC values of cells are selected randomly within the range of %92-99 so voltage imbalances are occurred. The type of battery cells used in simulation study is Lithium-ion. The capacity of LBP is 110 amp-hour. Charging and discharging operations are performed with the use of current sources. These sources are limited to four ampere in the simulation model. Nominal voltage of each cell is 3.7 V. In total, system voltage of LBP used in simulation study is 650 volt. AcBC model's parameters which are used in Matlab/simulink are given in table 5.1. AcBC's performance to eliminate voltage imbalances in battery modules is shown in figure 5.8 and figure 5.9.

In the first case study, ctb is supplied with the usage of first four cells of first sub-module. The system performance of the first case study is demonstrated in figure 6.8. Results show that balancing time of the AcBC is 25000 seconds.

Table 5.1. The parameters of simulation model (Study 1)

Parameters	**Values**
Battery Type	Li-ion
Battery Pack Capacity	110 Ah
Battery Pack Voltage	650 V
Sub-Modules	22
Series Modules	11
Series Cells	176
Nominal Cell Voltage	3.7 V
Charge/Discharge Currents	± 4 A

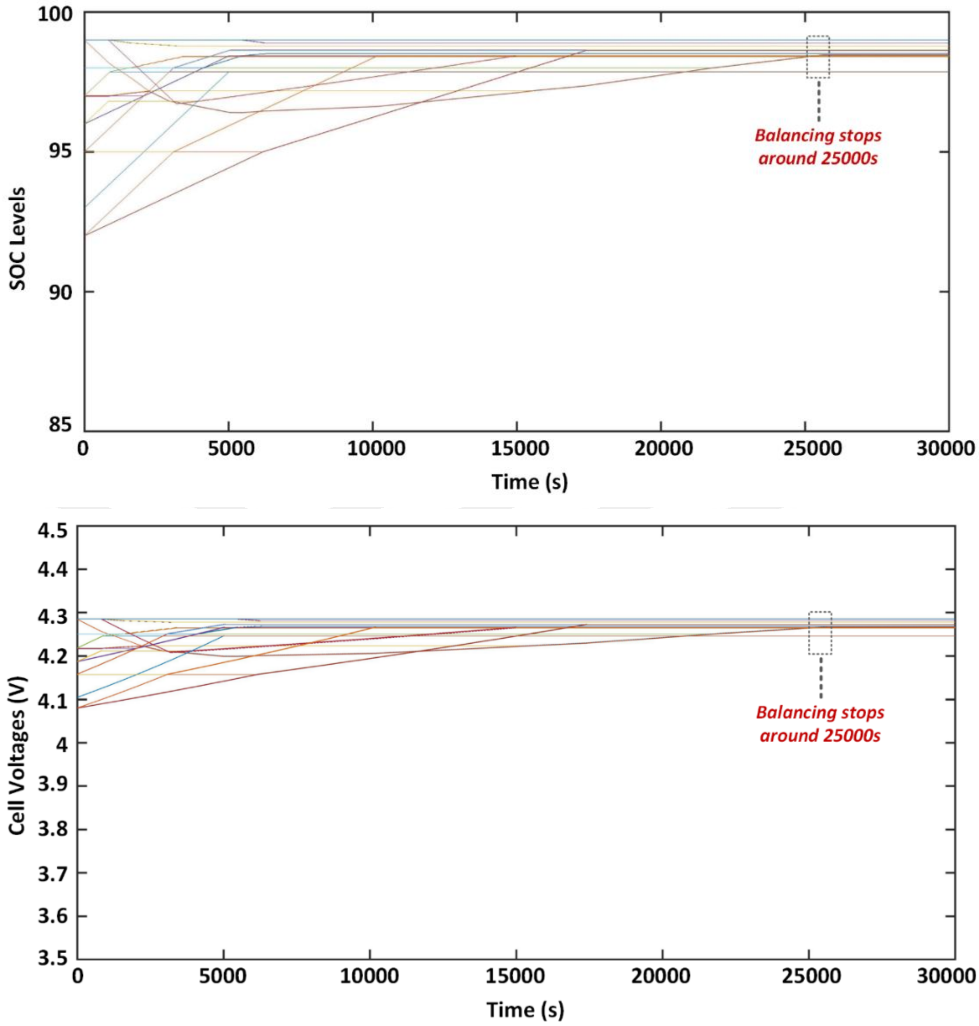

Figure 5.8. The simulation results of case 1 (presented model)

In the second case study, ctb is supplied with the usage of the first cell of first sub-module. The system performance of the first case study is shown in figure 6.9. Results show that balancing time of the AcBC is 18000 seconds. When two results are compared, topology which has ctb supplied by the first cell of first battery sub-module has shorter balancing time so choosing of the second topology can be more appropriate for LBP system.

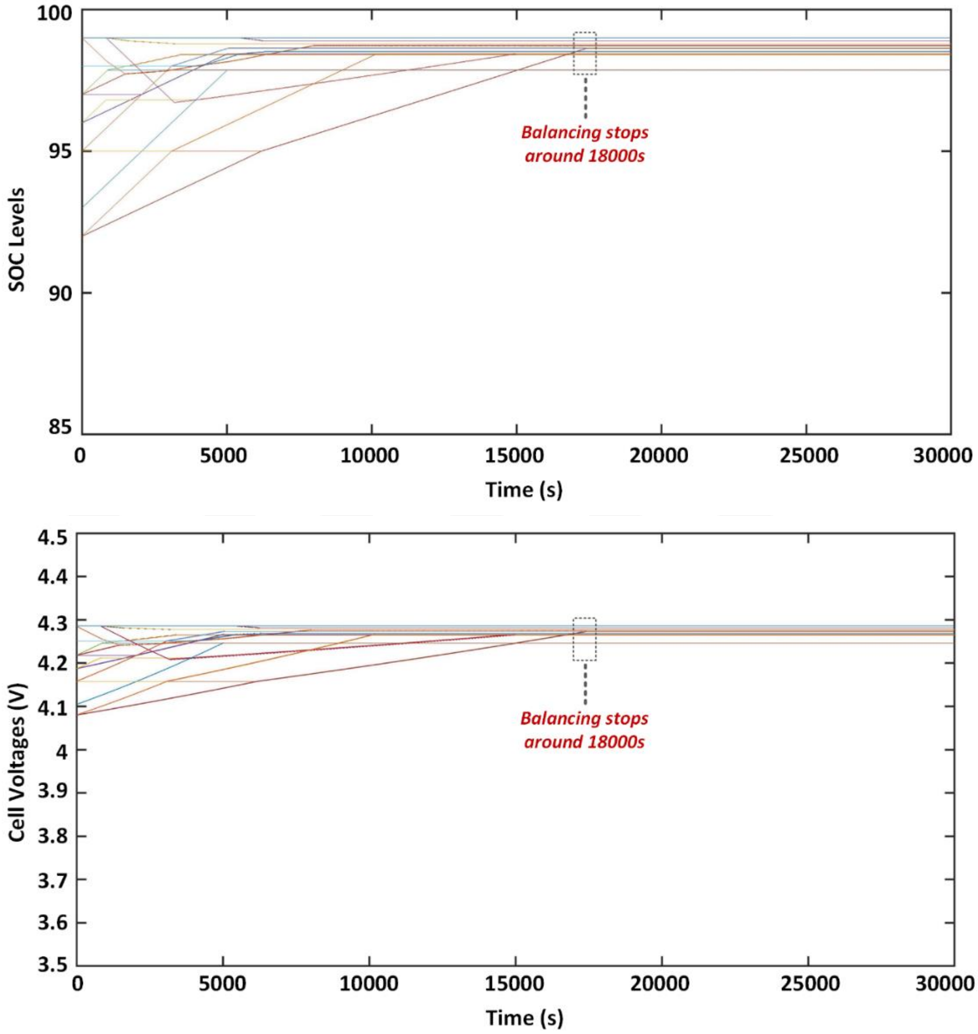

Figure 5.9. The simulation results of case 2 (presented model)

5.2.1.3. Study 1’s Conclusion

In the thesis, AcBC which has feature such as concurrent charge transfer at the same time is proposed for LBP. Simulation study of LBP is investigated with the usage of Matlab-Simulink. Since the simulation model of eleven modules has high run time and complexity, BiFLCs-Swms combination is carried out with a simple model of current sources. The main objective of the presented topology is to investigate system performance with different SOC values for LBP. The balancing performance of AcBC is tested with two case-studies. It is seen from the simulation results that the topology with cts which is supplied by the first four cells of the first sub-module has longer balancing time than the topology with cts which is supplied by the first cell of first sub-module. Usage of the cells as cts eliminate the need for auxiliary battery. Therefore, this approach might be considered as an improvement in existing topologies.

5.2.2. Study 2: A New and Fast Balancing Algorithm for LBPs

Topology presented in the article, which is published by Narayanaswamy et al. (2017), uses individual BiDC converter for each cell, and it is not compatible with LBP packs due to high cost. Topology design given in the article, which is published by Ouyang et al. (2018), has (n-1) number of dc-dc converters for n number of battery cells are used and an additional dc-dc converter is employed to equalize cells faster. Thus, the related topology is considered as expensive for LBPs. AcBCs presented in the articles, which are published by Kutkut (1998); Pascual and Krein (1997); Kauer et al. (2015), doesn't have non-neighbor balancing and also bidirectional power flow capability while AcBCs proposed in the articles, which are published by Lukasiewycz et al. (2014); Kauer et al. (2013), doesn't have full percentage of concurrent charge transfers. Table 5.2 shows the performance goals of some active balancing topologies. As it is understood from table 5.2, AcBSs, which are published by Narayanaswamy et al. (2017); Shah et al. (2018), are suitable for LBPs, when performance-based features are considered. However total number of switches are too high in AcBC of Narayanaswamy et al. (2017) and also it will require a dc-dc converter for each cell. Therefore a total of 176 dc-dc converter will be employed for LBP. On the other hand, the AcBC used by Shah et al. (2018) requires 2 BiDC converters for 16 cells. Consequently the topology used by Shah et al. (2018) is ideal because of the cost-effective and performance but algorithm can be improved. Starting from this part of the thesis, the algorithm which is used by

Shah et al. (2018) will be called the existing approach. Since it is necessary to consider performance in newly developed balancing topologies, this thesis also includes performance-based features such as non-neighbor Balancing and Percentage of concurrency. The main aims of the proposed thesis are; (i) to develop an algorithm that is adaptable to cell-to-cell balancing which is the cost-effective for LBPs of EHCV, (ii) to perform fast balancing (iii) to provide multiple charge transfers simultaneously between battery modules which is crucial for EHCVs which are equipped with LBP.

Table 5.2**.** Comparison of AcBCs based on performance goals (Study 2)

Performance Goals	***Non-Neighbor Balancing***	***Bidirectional Power Flow***	***Full percentage of concurrent ccharge transfers***	***Total Number of Switches***	***Suitable for LBP***
Proposed	✓	✓	✓	28	✓
(Shah et al., 2018)	✓	✓	✓	26	✓
(Narayanaswamy et al., 2017)	✓	✓	✓	128	✓
(Kauer et al., 2013)	✓	✓	✗	144	✗
(Lukasiewycz et al., 2014)	✓	✓	✗	192	✗
(Kauer et al., 2015)	✗	✗	✗	80	✗
(Pascual and Krein, 1997)	✗	✗	✓	64	✗
(Kutkut, 1998)	✗	✗	✓	32	✗
	Features				

This model has small differences than the previous model (Study 1 model). However with help of new algorithm, second model is more convenient for LBPs. In this model, new balancing algorithm compatible with active balancing topology is developed for high power applications endowed with LBPs. To evaluate the proposed balancing algorithm, balancing topology which consists of battery modules and BiDC converters equipped with switch matrix have been conducted by using Matlab/Simulink. The presented model provides a bidirectional power flow to perform charging/discharging operations between source/destination cells. BiDC converter provides the isolation and charge transfer between battery cells and the bus. One module consists of 2 submodules and each submodule consists of 8 series cells which is shown in figure 5.10. The LBP, that features a nominal voltage of 650 V and a capability of 110 Ah, is modeled with eleven series connected modules, and each module consists of sixteen series connected cells. Vehicle battery (24 volt) supplies CTB and balancing operation is provided via CTB. An important feature of the proposed algorithm compared to existing algorithms is that even if the vehicle battery is used as CTB, there is no loss in the life-cycle of the 24 volt battery. The balancing time in LBPs can be reduced significantly by performing charge transfer between different cells simultaneously in each battery sub-module. The Switch matrix is utilized to link between related cells and the CTB through the BiDC converter. Switch matrix contains two switching structure which consists of 9 cell switches (CSWs) and 4 polarity switches (PSWs). CSWs are operated by choosing the related cell's switches to transfer excess energy to the destination cell with the help of dc-dc converter; similarly PSWs are operated considering polarity of associated cells which is detailed in the next chapter. The general diagram of the AcBS for EHCV is given in figure 5.11.

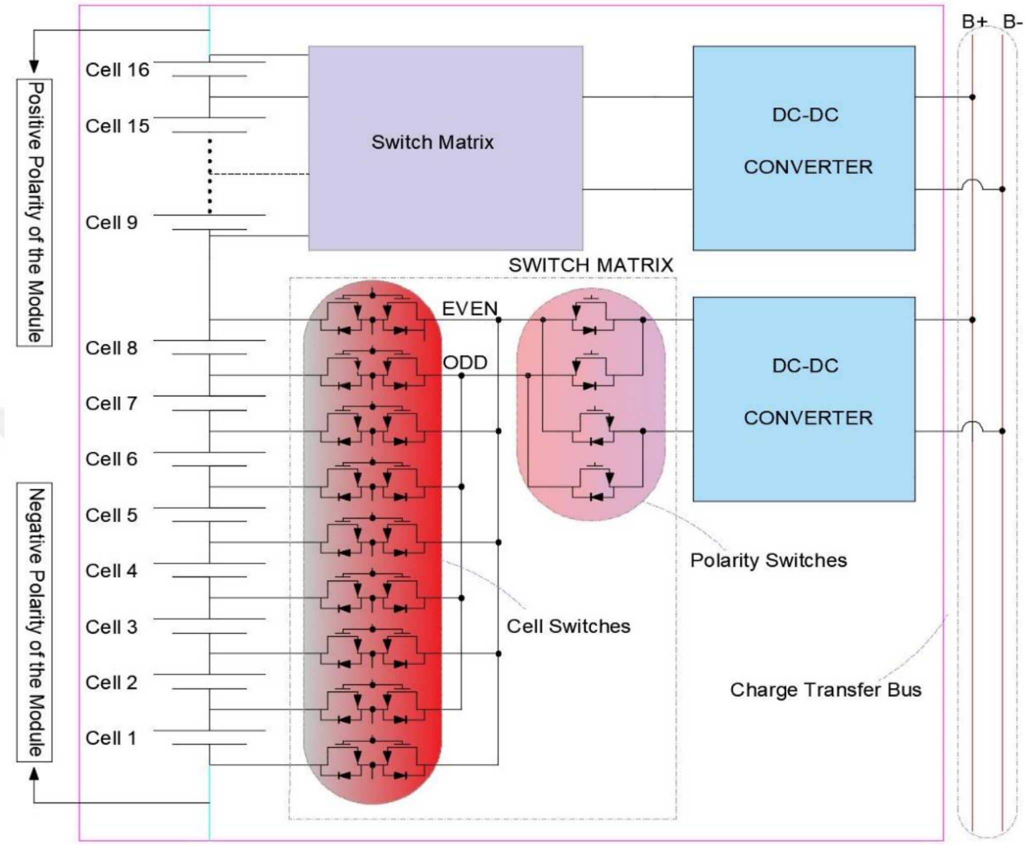

Figure 5.10. Simulation model of one module with BiDC converter with proposed algorithm

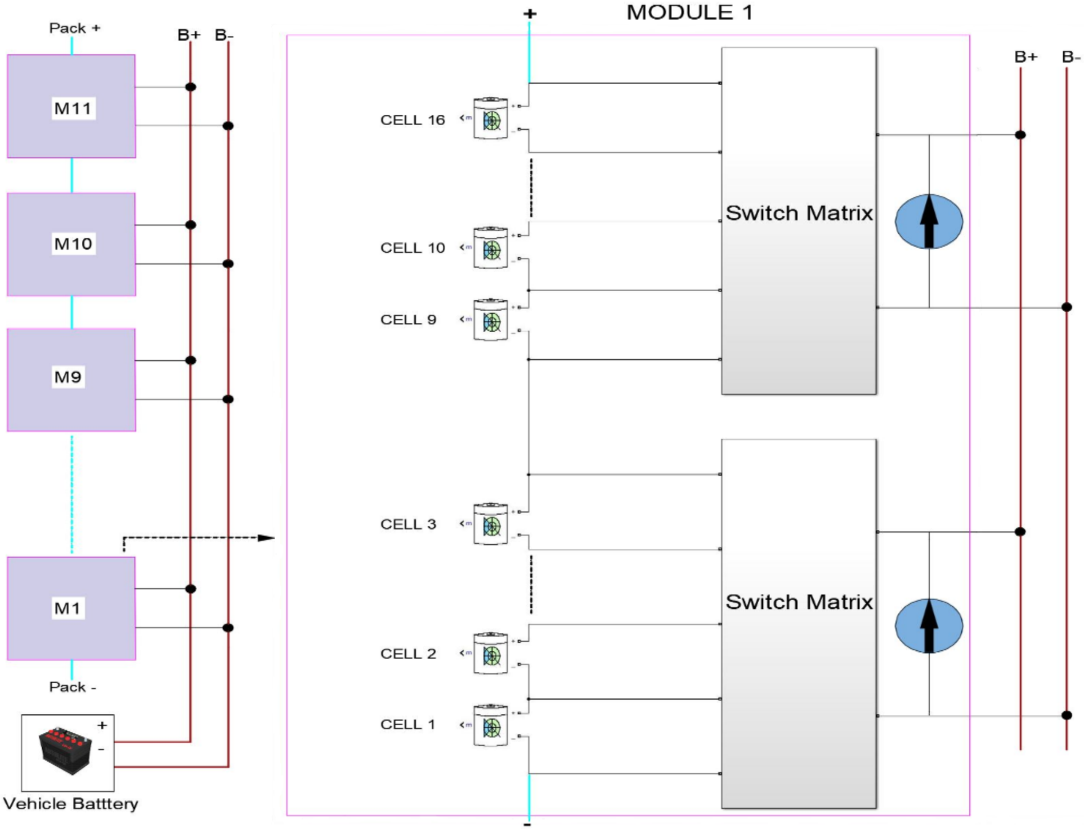

Figure 5.11. The simulation model of AcBS (model with proposed algorithm)

5.2.2.1. Study 2's Control Scheme

The proposed balancing algorithm determines the balancing scenario based on the voltage imbalances in each submodule. Voltages of 176 cells are monitored by controller unit for determining the maximum and minimum cells for each sub-module independently. Since each battery module consists of 2 submodules, control unit determines two cells with highest and two cells with lowest voltages per battery module. For the system, 22 maximum and 22 minimum cells are selected and 22 maximum values are sorted among themselves from highest to lowest by control unit. Similary 22 minimum values are sorted among themselves from lowest to highest. The algorithm matches the highest cell voltage between 22 maximum values and the lowest cell voltage between 22 minimum values. Second highest cell voltage from 22 maximum values and second lowest values between 22 minimum values are matched and this sorting continues like this. Thus, 22 pairs are formed and multiple balancing process is performed in the same module or between modules simultaneously. As shown in equation 5.5, balancing process is initialized if the difference between the pair of maximum cell voltage and minimum cell voltage is more than 10mV. With the usage of equation 5.6, the proposed algorithm decides the direction of power transfers between battery sub-modules. The difference between Vmin_mi and average of sub-module voltages (Vavg_mi) and the difference between Vmax_mi and Vavg_mi are considered. Excessive energy is transferred from maximum cells in submodules to minimum cells in other submodules with the help of BiDC converter via CTB. To provide energy transfer between selected cells, switch matrix's switches must be enabled considering the control signals (On /off). However in LBPs, control of these switches are not easy; it is only possible with using such a switching rule proposed in this paper.

$$\begin{aligned} &balancing\ starts \quad V_{max_{mi}} - V_{min\_mi} > 1mV \\ &balancing\ ends \quad V_{max_{mi}} - V_{min_{mi}} \leq 1mV \end{aligned} \tag{5.5}$$

$$\begin{aligned} &discharge\ operation \quad V_{max_{mi}} - V_{avg_{mi}} > V_{avg_{mi}} - V_{\min\_mi} \\ &charge\ operation \quad V_{max_{mi}} - V_{avg\_mi} < V_{avg\_mi} - V_{\min\_mi} \end{aligned} \tag{5.6}$$

In one battery module, up to x connected cells in series is symbolized as set B = {1, 2, …, x} where x is maximum sixteen. There are m series connected battery modules in the considered LBP. In this paper battery modules are smybolized as M = { 1,...., m}. Every cell x ∈ B and x ∈ M is linked with dc-dc converter and Z is defined as integer. Polarity switches are symbolized as psw1, psw2, psw3, psw4. Set of cell switches are symbolized as csw^m = {csw_x^m, csw_{x+1}^m, csw_{x+2}^m, csw_{others}^m}.

Charge transfer process is specified by Q. It includes various charge transfer pairs t=F × S. F represents set of first eight cells in the module. In similar S represents set of second eight cells in the module. F and S are subset of B, these are disjoint and there must be a domain too. The domain is formed by every transfer pair which is shown by d(t)={Min(n|n ∈ F∪ S),...,Max(n|n ∈ F∪ S)}. Depends on the transfer process Q, switch control specification of switch matrix's mosfets is s(Q, csw) ∈{ 0,1}. 0 shows that switch is off and 1 indicates that switch is on. In order to obtain the necessary control signals of switch matrix, switching rule table is presented (see table 5.3). As it is seen from table 5.3, the Switching rule table presents five conditions. In the first two conditions, the voltage of the selected cell is higher or lower (finding maximum or minimum voltage value) in than the others in its own module and location of this cell is in the first submodule (cell 1 to cell 8) so according to proposed switching algorithm, cell number x and x+1 are actuated with signal 1. Polarity switches operate according to whether the selected cell is odd or even. The difference between the two conditions is that the selected cell is an odd number in the first condition and an even number in the second condition. For example if the selected cell is even number (cell 4), top and bottom polarity switches (psw1, psw4) are actuated with signal 1 and cell switch 4 and cell switch 5 are enabled with signal 1 because of the switch rule of x and x + 1. In the condition 3 and condition 4, the voltage of the selected cell is also higher or lower than the others in its own module but location of this cell is in the second submodule(cell 9 to cell 16) so according to proposed switching algorithm, cell number n+1 and n+2 are actuated with signal 1. The difference between the two conditions is that the selected cell is an odd number in the third condition and an even number in the fourth condition. For example if the selected cell is odd number (cell 13), middle polarity switches (psw2, psw3) are actuated with signal 1 and cell switch 14 and cell switch 15 are enabled with signal 1 because of the switch rule of x+1 and x+2. Finally, when no balancing is needed, condition 5 occurs. Voltage measurements are taken with 10 ms sample time, while switch positions are updated in every 8 seconds. The flowchart of the balancing algorithm is shown in figure 5.12.

Table 5.3**.** Switching Rule Table (Study 2)

Conditions	Description	Switching Configuration: Cell switches				Switching Configuration: Polarity switches			
		csw_{x}^{m}	csw_{x+1}^{m}	csw_{x+2}^{m}	$csw_{xothers}^{m}$	*PSW1*	*PSW2*	*PSW3*	*PSW4*
1) ∃t∈Q: n∈F ∩ n∈2Z+1	Selected cell is odd number and Location of the cell is in the first sub-module	1	1	0	0	0	1	1	0
2) ∃t∈Q: n∈F ∩ n∈2Z	Selected cell is even number and Location of the cell is in the first sub-module	1	1	0	0	1	0	0	1
3) ∃t∈Q: n∈S ∩ n∈2Z	Selected cell is odd number and Location of the cell is in the second sub-module	0	1	1	0	0	1	1	0
4) ∃t∈Q: n∈S ∩ n∈2Z	Selected cell is even number and Location of the cell is in the second sub-module	0	1	1	0	1	0	0	1
5) ∃t∈Q: n∉**d(t)**	No Charge Transfer	0	0	0	0	0	0	0	0

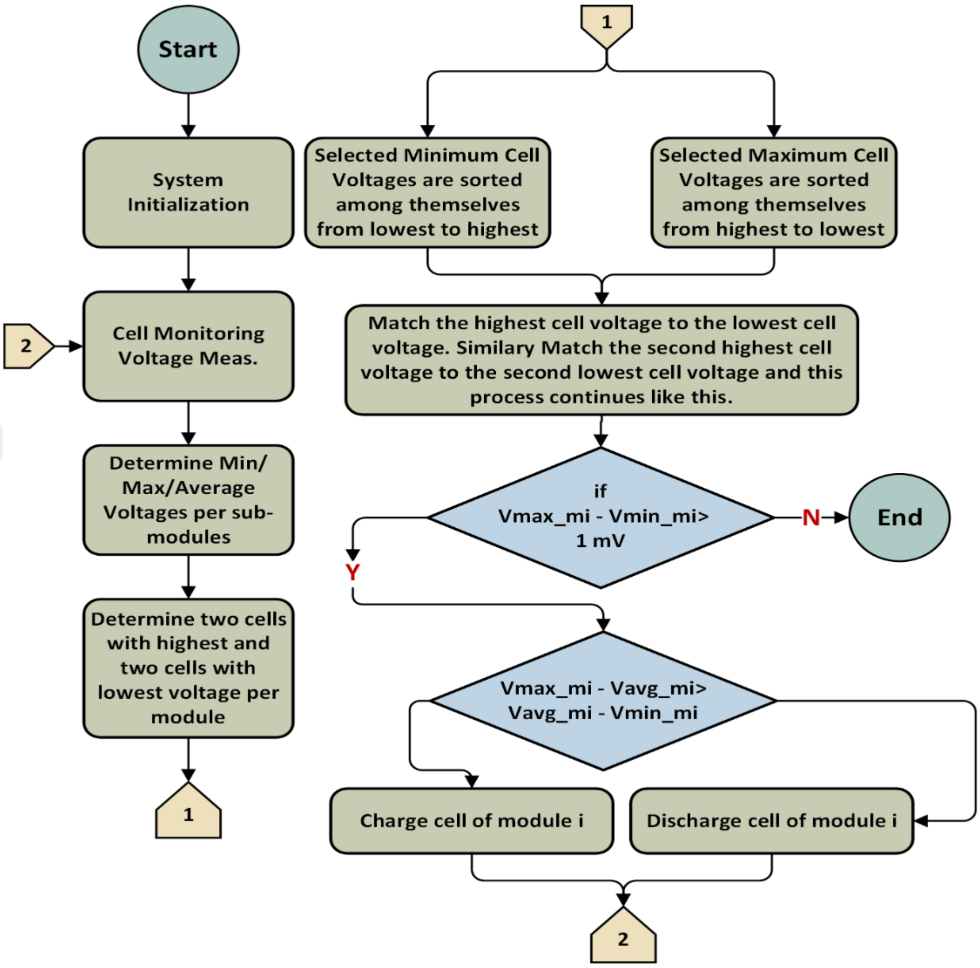

Figure 5.12**.** The flowchart of the proposed algorithm

5.2.2.2. Study 2's Simulation Results

The balancing performance of the presented system is tested with comparing two algorithms (proposed algorithm and existing algorithm) using a LBP consisting 176 series cells which have been characterized in different SOC levels between the range of 93% and 98%. The cells used in the simulation study are Lithium-ion (Li-ion) with a capacity of 110 Ah and a nominal voltage of 3.7 V. The charge/discharge operation is performed using current sources that are limited to 4 A. The design parameters of the simulation model are given in table 5.4. One of the difference between the topology the topology used by Shah et al. (2018) and the topology presented in this paper is two dc-dc converters for each module (16 battery pack), while AcBS given by Shah et al. (2018) uses one dc-dc converter. The proposed algorithm is investigated with two case studies.

In the first case, all eight cells of each sub-module have different voltage levels and the initial voltage difference between maximum battery cell and minimum battery cell is 134 mV. The results for the first case are shown in figure 5.13 and 5.14. After the balancing process is finished, the difference between the maximum and the minimum battery cell voltages (voltage imbalance range) measured in the simulation results of the proposed algorithm is approximately 1.4 mV (See fig. 5.13). On the other hand, as a result of balancing performed using the existing algorithm, the final difference between maximum and minimum battery cell voltages reaches 39.3 mV as illustrated in fig. 5.14. Since the existing algorithm does not have the ability to transfer charge between modules, the balancing takes a long time as well as the final voltage difference between the maximum and minimum cell voltages cannot be sufficiently reduced in the pack. As can be seen from the results, the proposed algorithm yields better results in reducing imbalances between cells in a LBP. Fig. 5.15 shows the module 10 (randomly chosen between 11 modules) balancing results of the existing algorithm. As it is understood from the figure, the existing algorithm achieves good results on a module-based but the voltage imbalance range in the battery package increases for a case of series connected 11 modules. Even though it is considered on the basis of the module, the proposed algorithm yields better results with approximately 10 times the difference between the maximum and minimum cell voltages compared to existing algorithm. Moreover, balancing is performed within 7483 and 20914 seconds, respectively, with the proposed and existing algorithms. As can be seen from the results, there is nearly 3 times difference in the balancing times achieved by the developed algorithm. The algorithm proposed in this paper pairs the cells with the largest and the lowest voltage values to decrease voltage imbalances in modules. The pairing process is achieved with an additional dc-dc converter that allows dual-channel structure. Even if the number of dc-dc converters are equal in both topologies, the balancing time of the proposed algorithm is estimated to give better results. See figures 5.16-5.21 for more information on the active balancing results of the Case 1 study.

Table 5.4. The parameters of simulation model (Study 2)

Parameters	Values
Battery Type	Li-ion
Battery Pack Capacity	110 Ah
Battery Pack Voltage	650 V
Sub-Modules	22
Series Modules	11
Series Cells	176
Nominal Cell Voltage	3.7 V
Charge/Discharge Currents	± 4 A

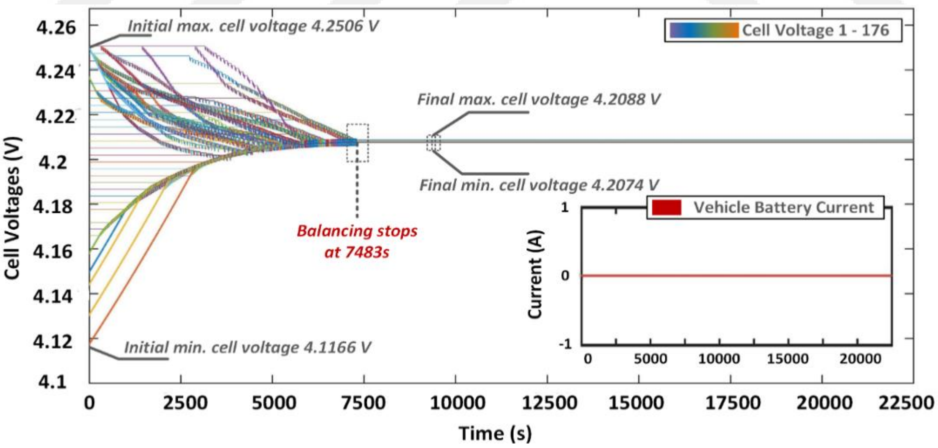

Figure 5.13. The simulation results of case 1 (Presented Algorithm)

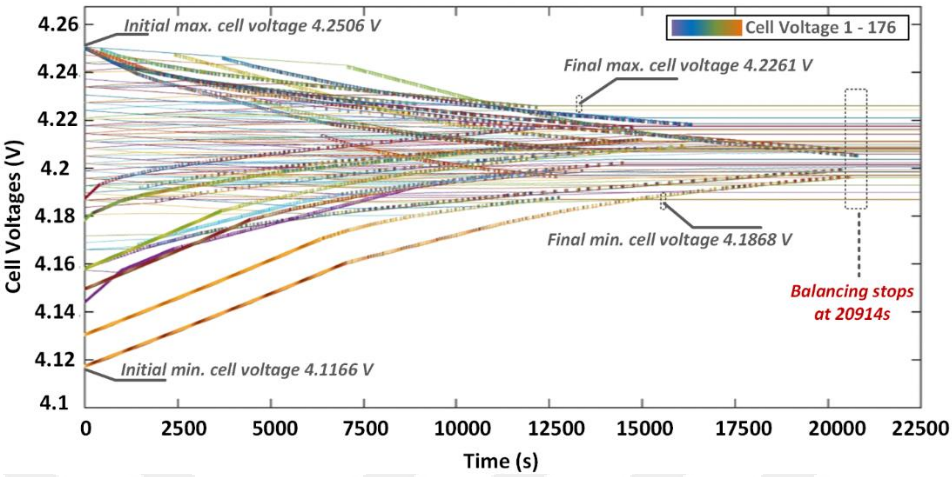

Figure 5.14. The simulation results of case 1 (Existing algorithm)

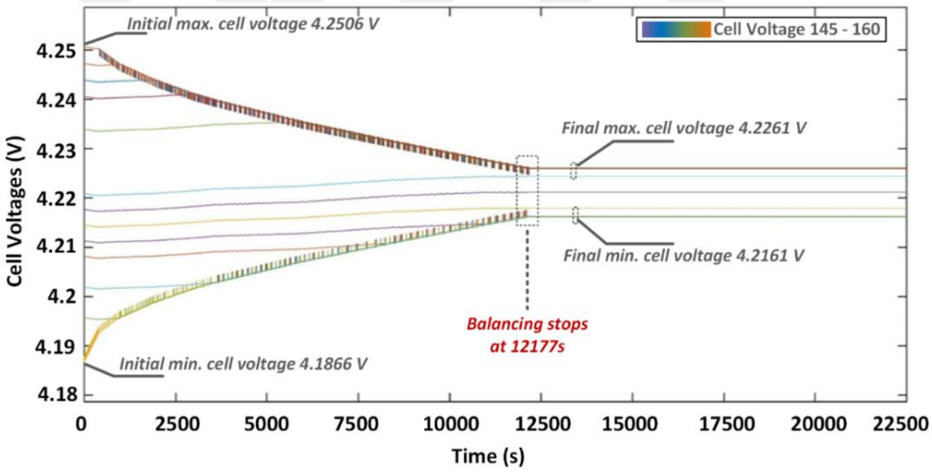

Figure 5.15. The simulation results of Module 10 /Case 1 (Existing Algorithm)

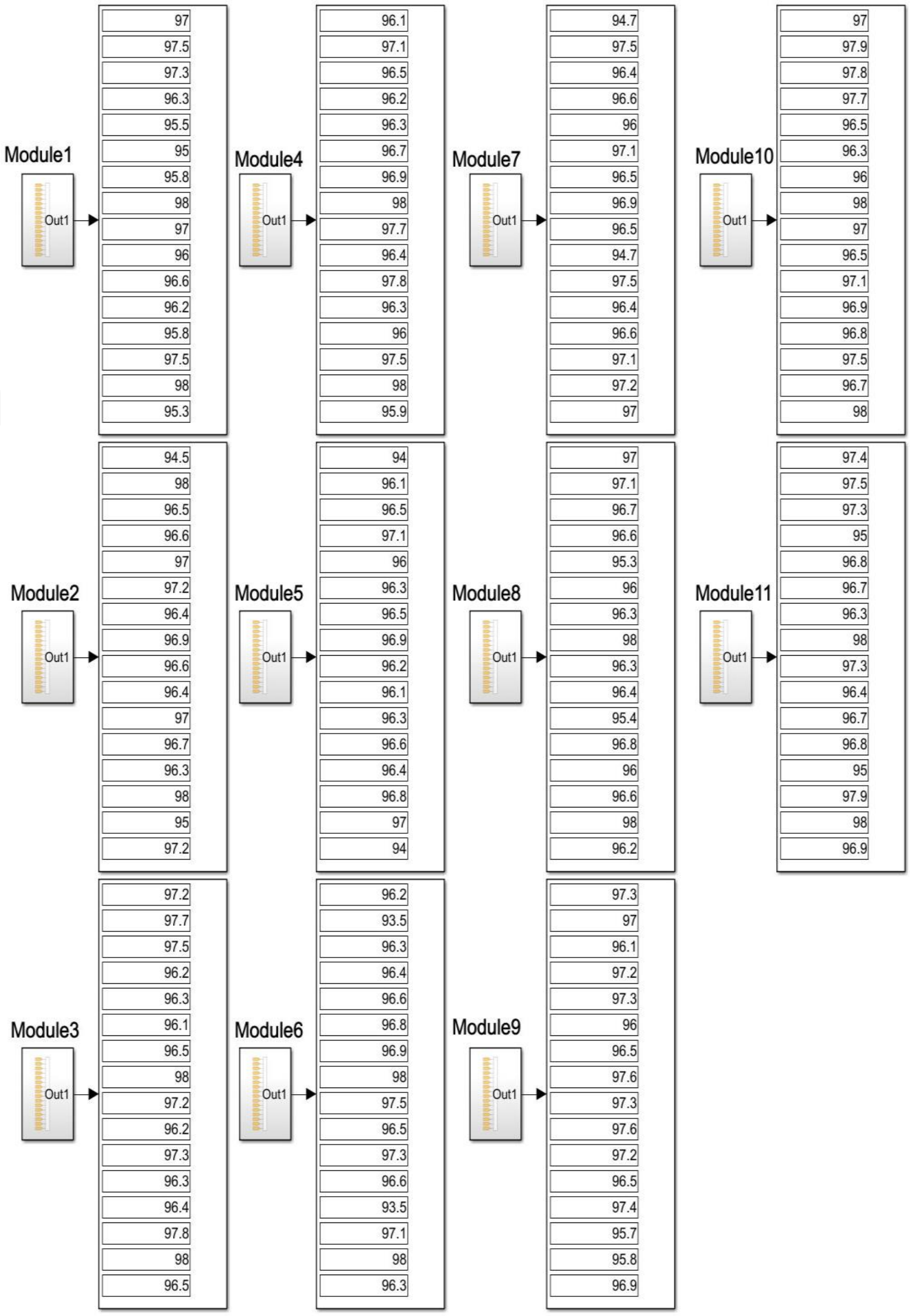

Figure 5.16. SOC levels before balancing operation (Case 1)

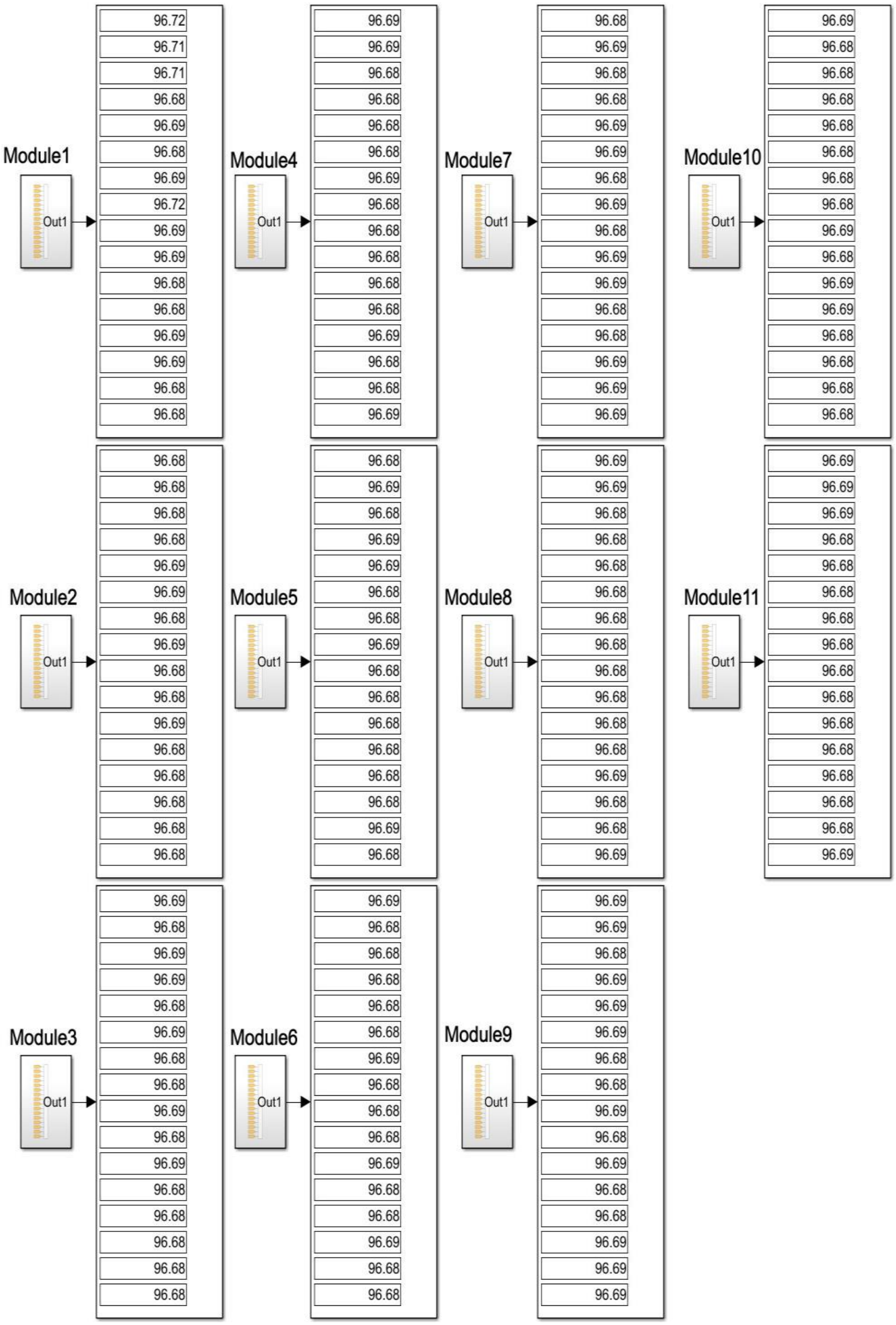

Figure 5.17. SOC levels after balancing operation (Proposed algorithm/Case 1)

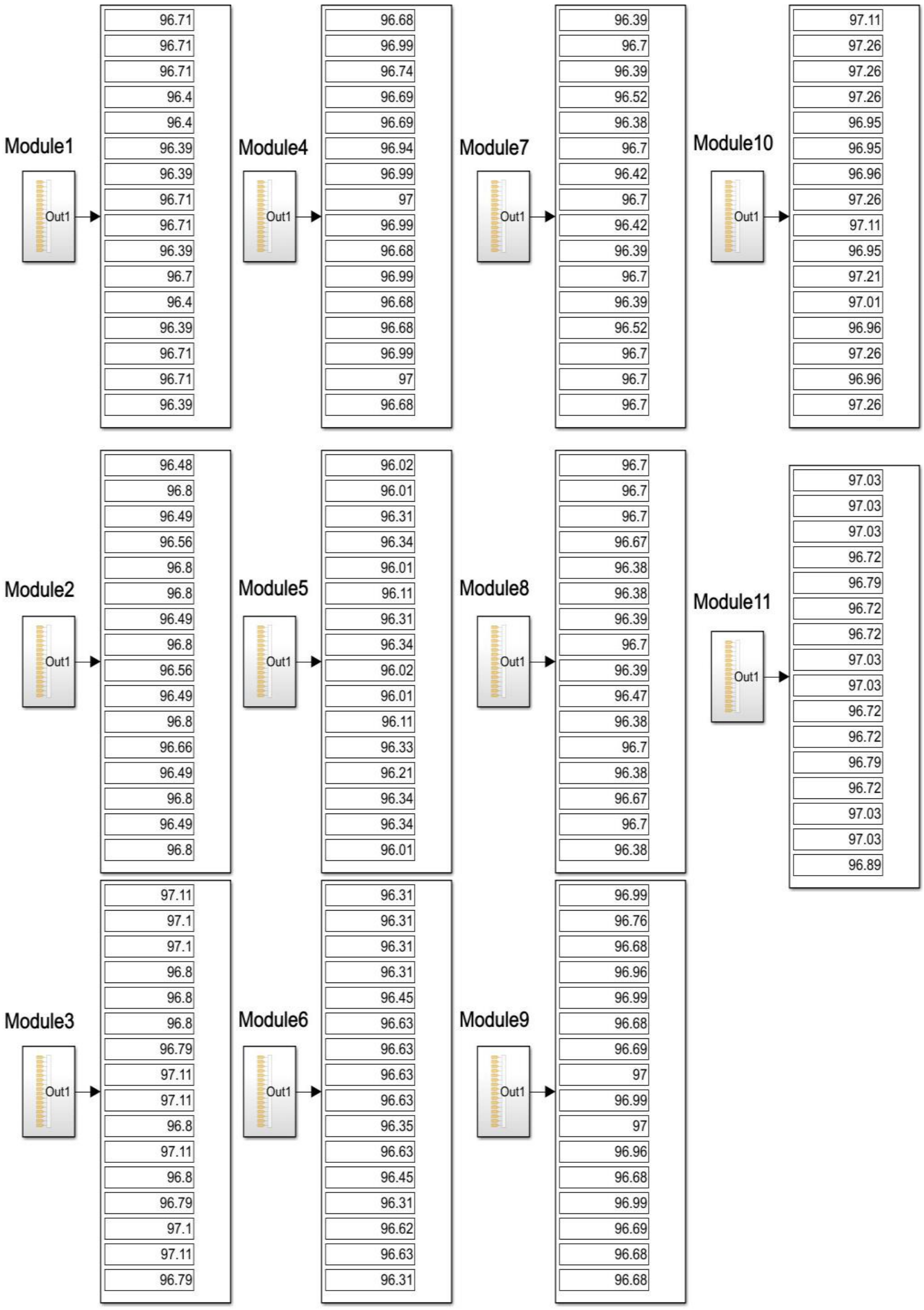

Figure 5.18. SOC levels after balancing operation (Existing algorithm/Case 1)

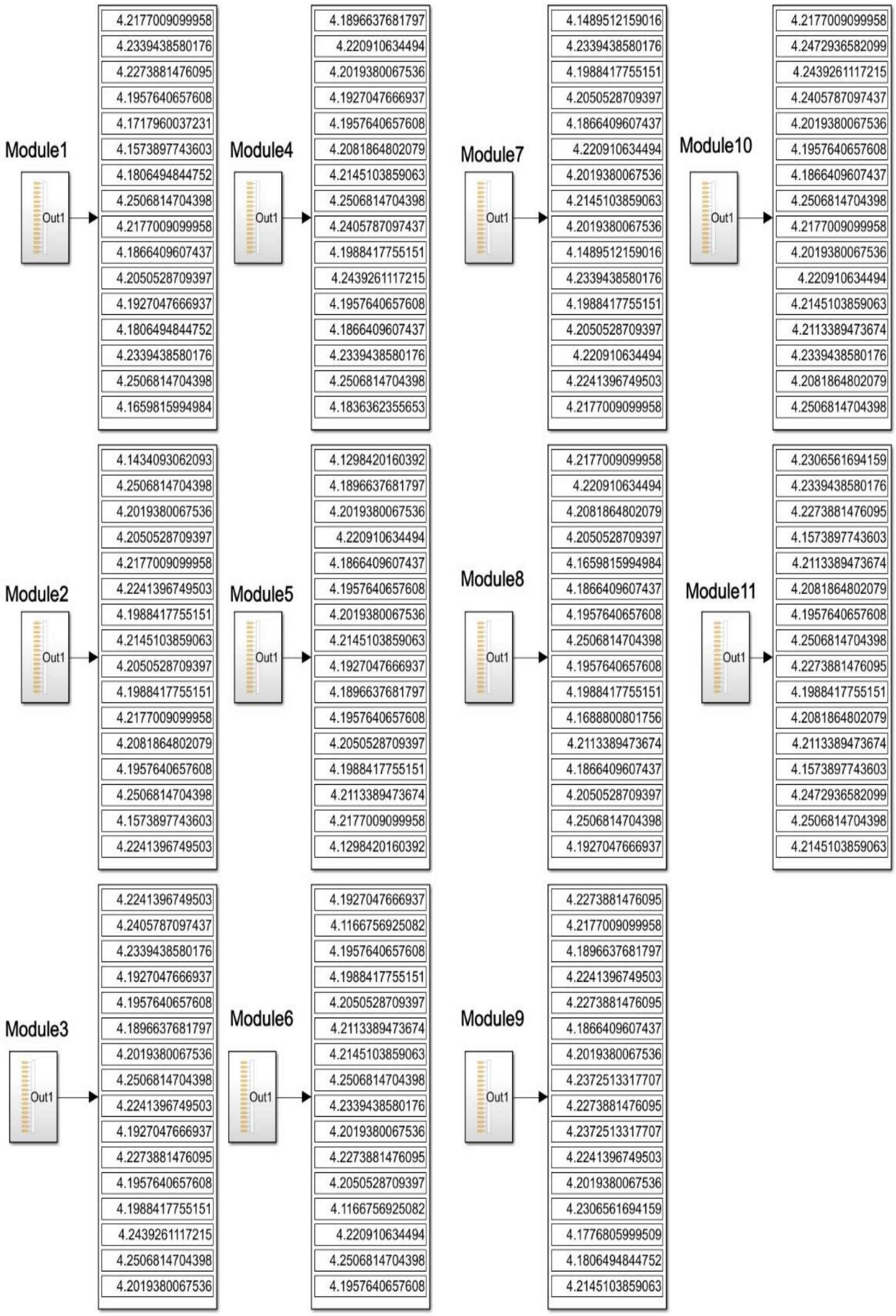

Figure 5.19. Cell voltages before balancing operation (Case 1)

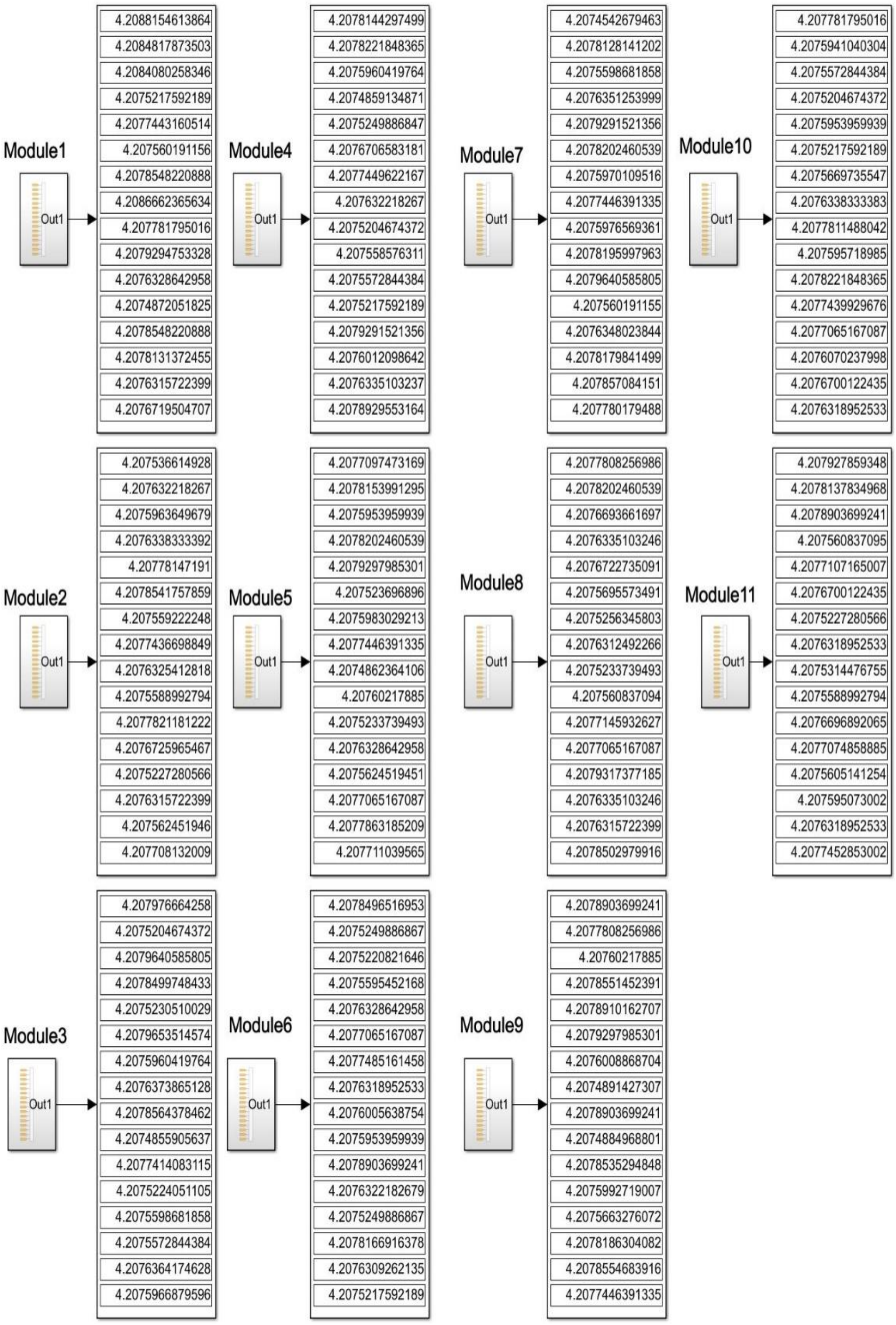

Figure 5.20. Cell voltages after balancing operation (Proposed algorithm /Case 1)

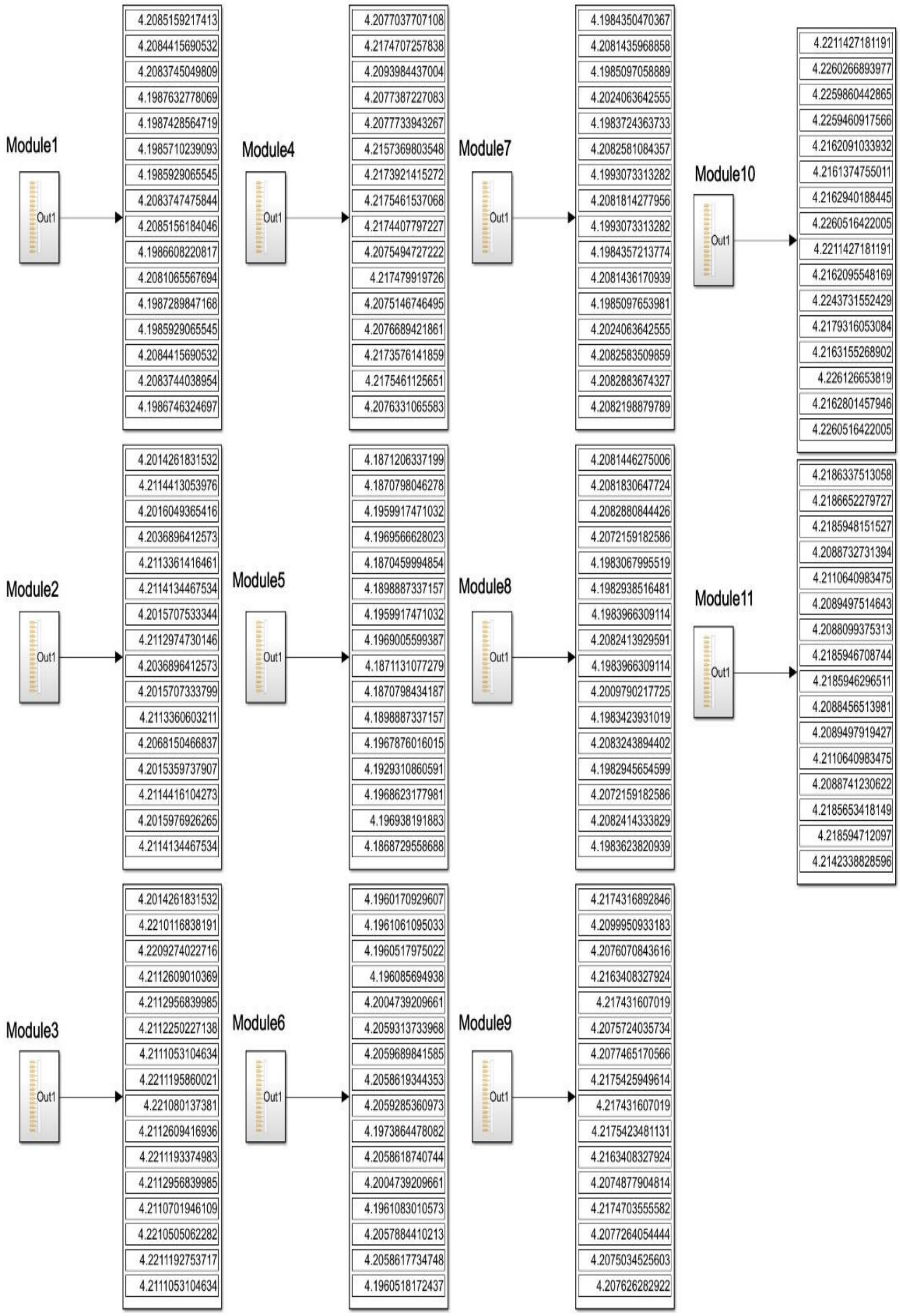

Figure 5.21. Cell voltages after balancing operation (Existing algorithm/Case 1)

In the second case, it's assumed that SOC values of 83 battery cells are the same (SOC value is 96.5) and 93 battery cells have different S0C values. Another difference from the 1st case that initial voltage difference between maximum and minimum cell voltage is 58.3 mV which is half of the initial voltage difference in the 1st case. The results for the second case are shown in figure 5.22 and 5.23. As result of balancing in proposed algorithm, maximum and minimum cell voltage difference is 0.8 mV (see fig. 5.22). In figure 5.23, balancing results of the existing algorithm is shown. As expected, the voltage imbalance range results are better than the results in the first case because of the reduced initial voltage imbalances. The results of cell voltage imbalance range after the balancing in LBP is 20.6 mV for existing algorithm. However, comparing two results show that proposed algorithm has far better results to overcome voltage differences because of having an advantage like concurrent charge transfers between modules or inside module. In addition, module 4 (selected randomly) balancing results are shown in figure 5.24 and final voltage imbalance range after the balancing process is 9.8 mV. The balancing time of the system designed with the algorithm proposed in Figure 5.22 is 5021 seconds and the balancing time of existing approach shown in Figure 5.23 is 12526 seconds. As can be seen that there is more than 2 times difference in the balancing times of algorithms. Finally, comparing proposed algorithm with the other articles which are published by Ouyang et al. (2018); Park et al. (2009); Phung et al. (2011), proposed algorithm balancing speed seems to be slow but it is not true in reality. Since batteries used in these articles have small capacities like 2 Ah, 4 Ah, and 1 mAh respectively, it is normal to have a balancing time around 1200-3000 seconds. In addition, these studies are verified with small scale systems which have maximum 15 battery cells. On the other hand, in this thesis, a simulation study is done for all 176 cells that have a capacity of 110 Ah which is the real case for EHCVs. See figures 5.25-5.30 for more information on the active balancing results of the Case 2 study.

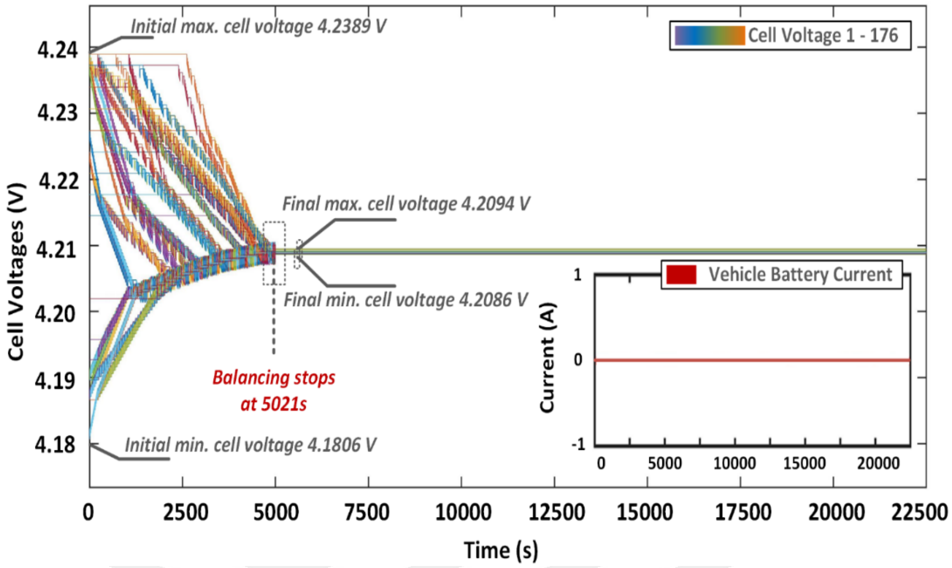

Figure 5.22. The simulation results of case 2 (Presented Algorithm)

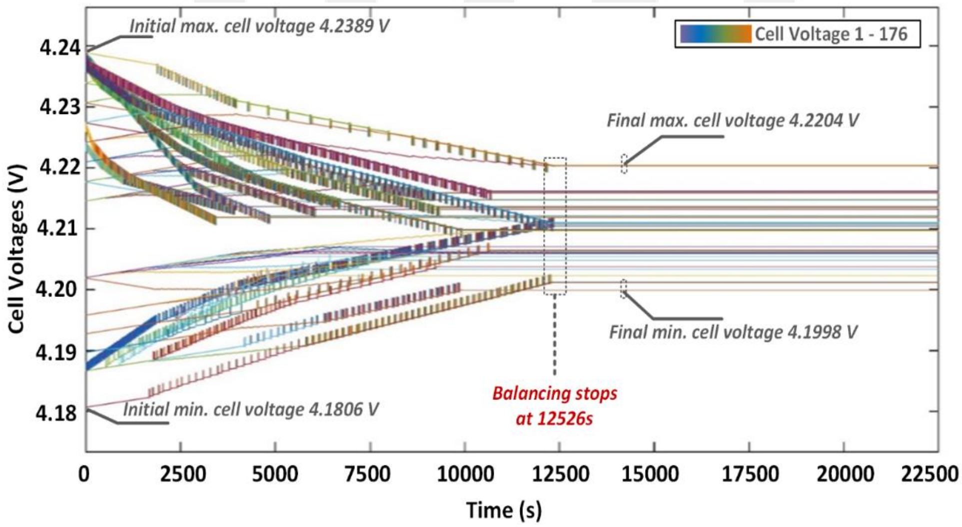

Figure 5.23. The simulation results of case 2 (Existing algorithm)

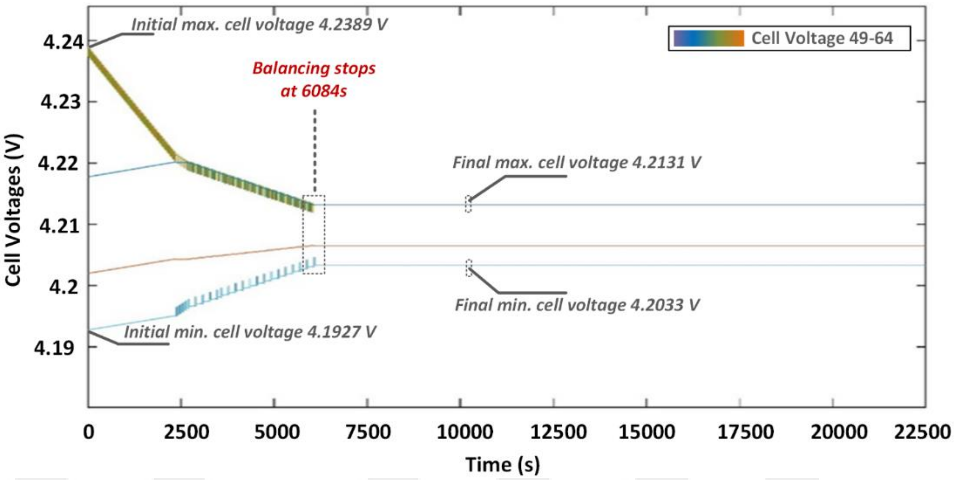

Figure 5.24. The simulation results of Module 4 /Case 2 (Existing Algorithm)

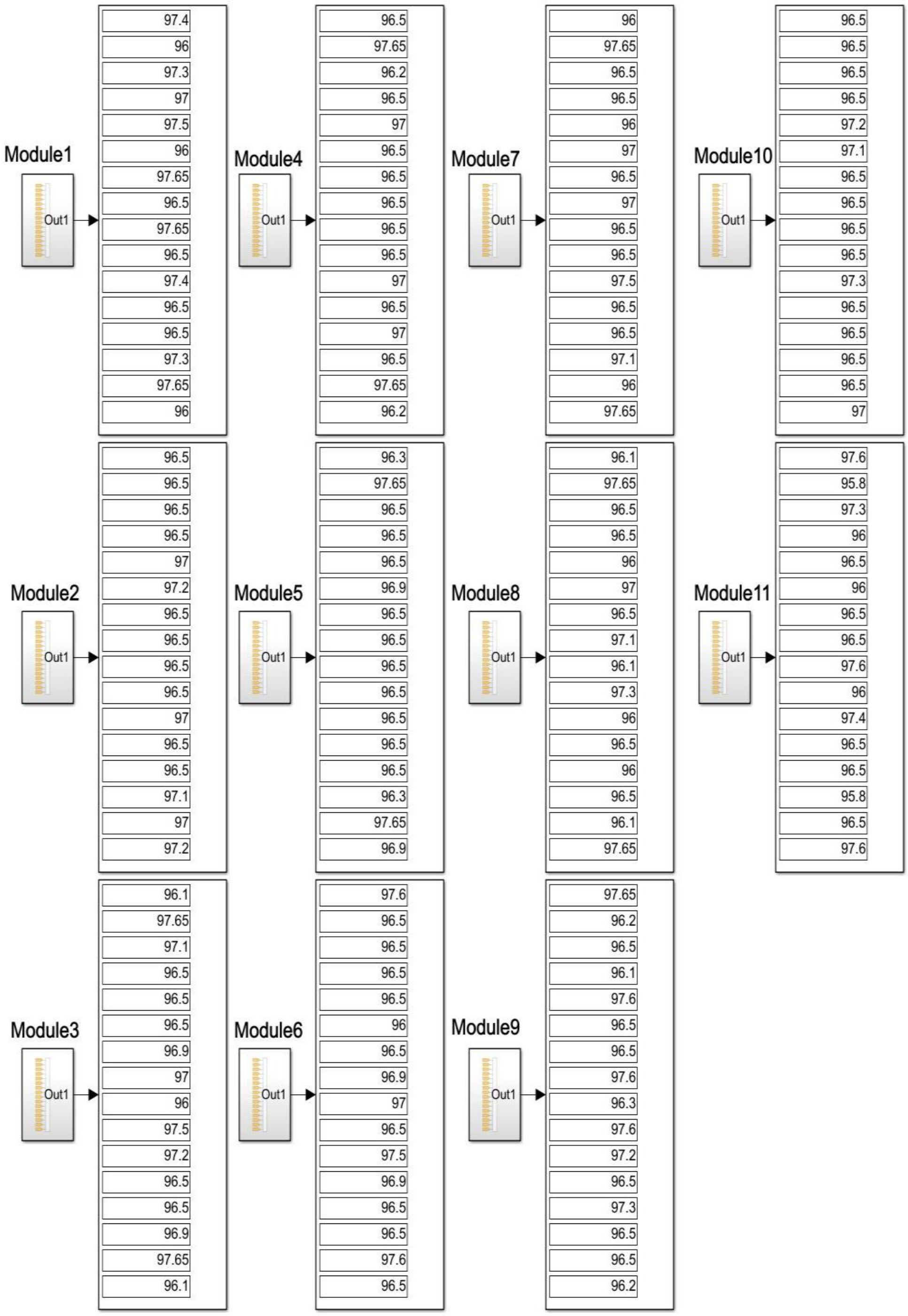

Figure 5.25. SOC levels before balancing operation (Case 2)

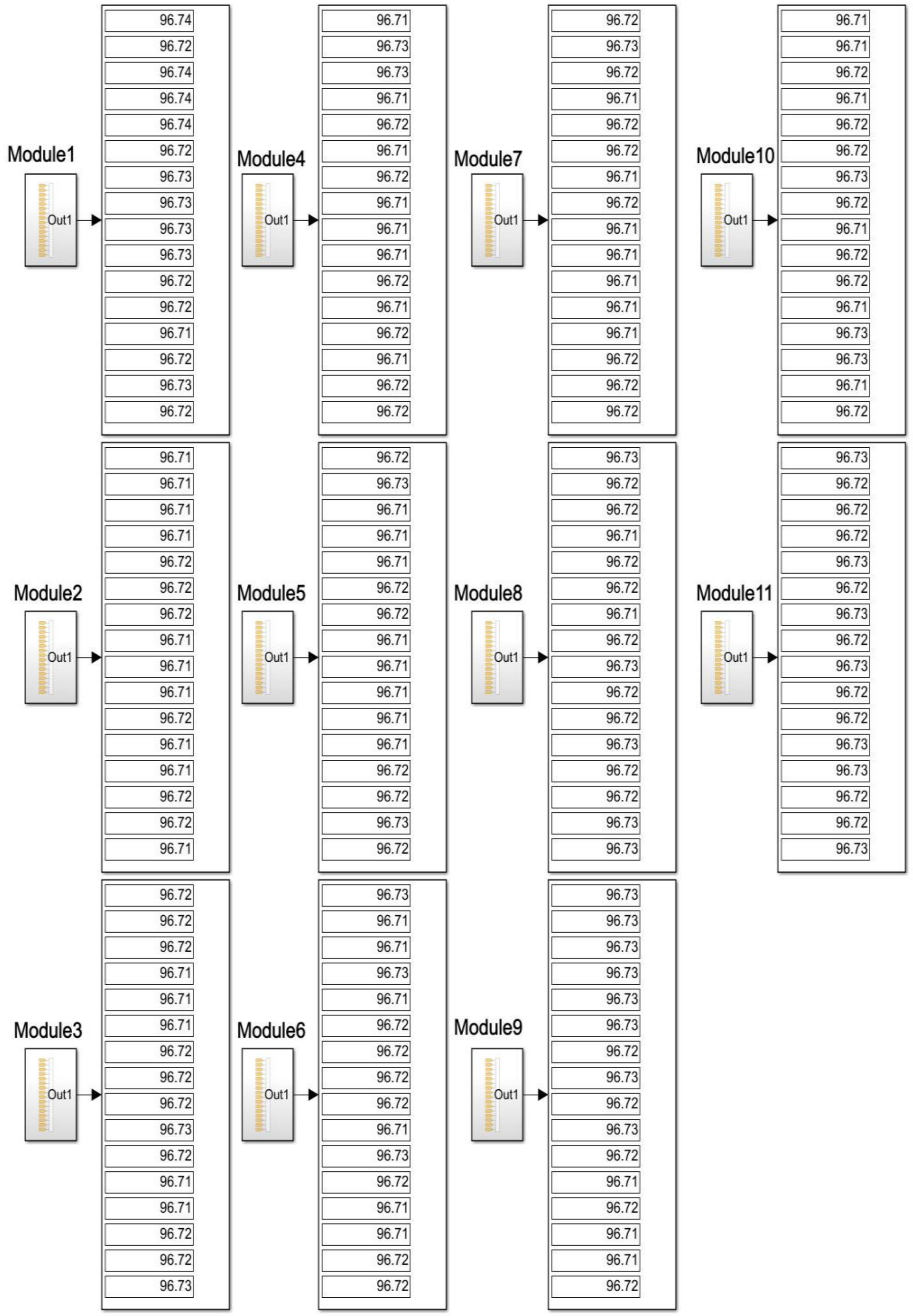

Figure 5.26. SOC levels after balancing operation (Proposed algorithm/Case 2)

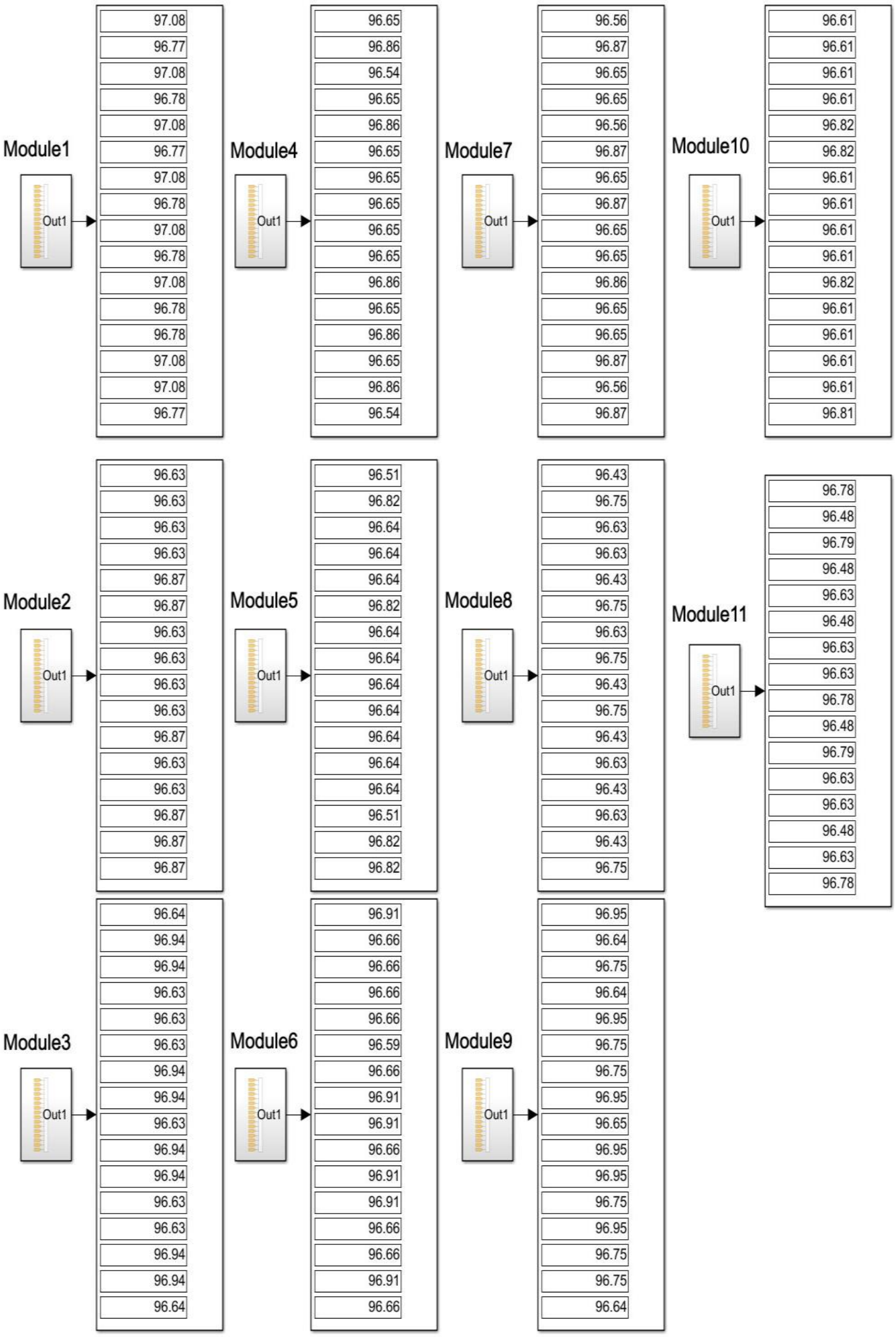

Figure 5.27. SOC levels after balancing operation (Existing algorithm/Case 2)

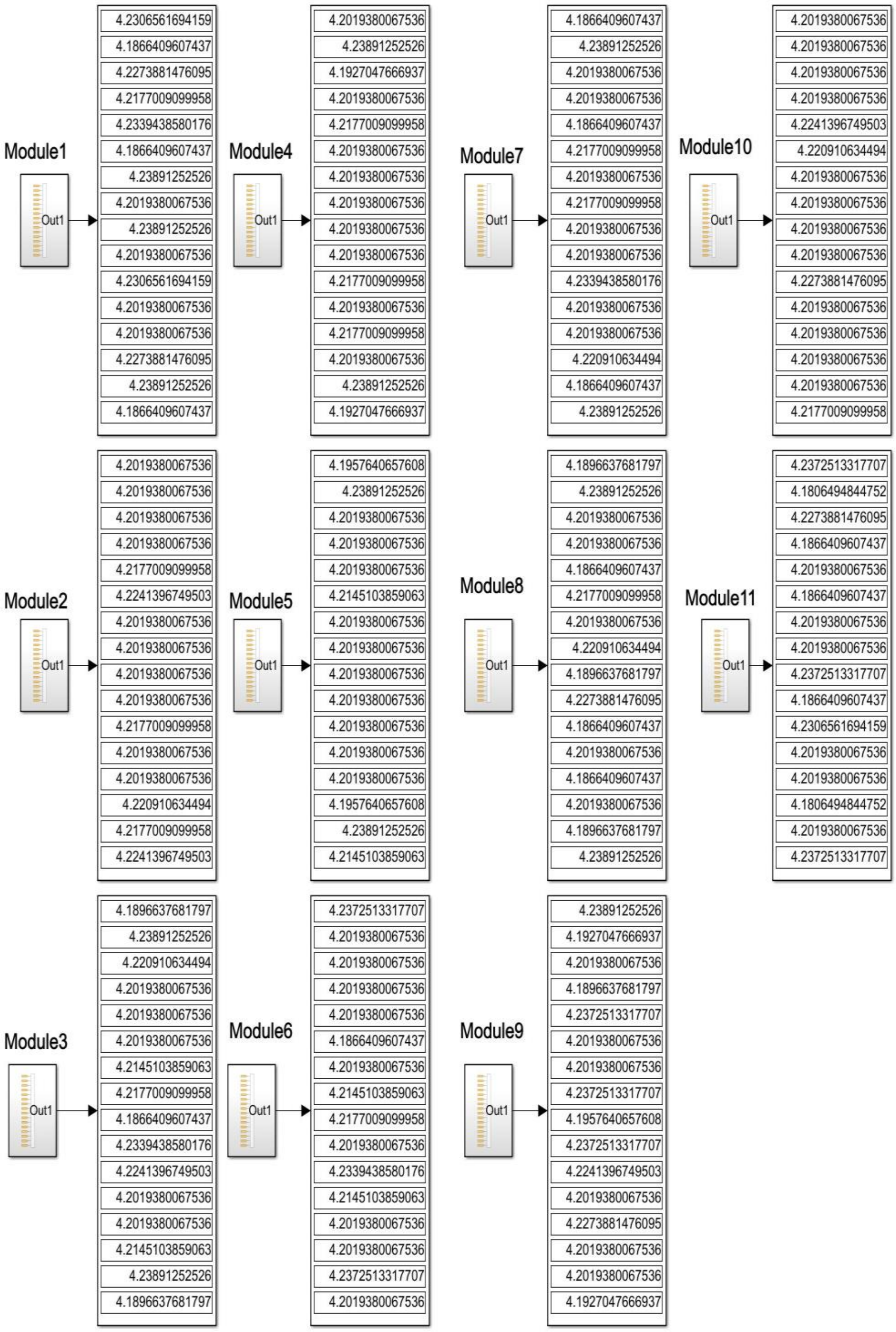

Figure 5.28. Cell voltages before balancing operation (Case 2)

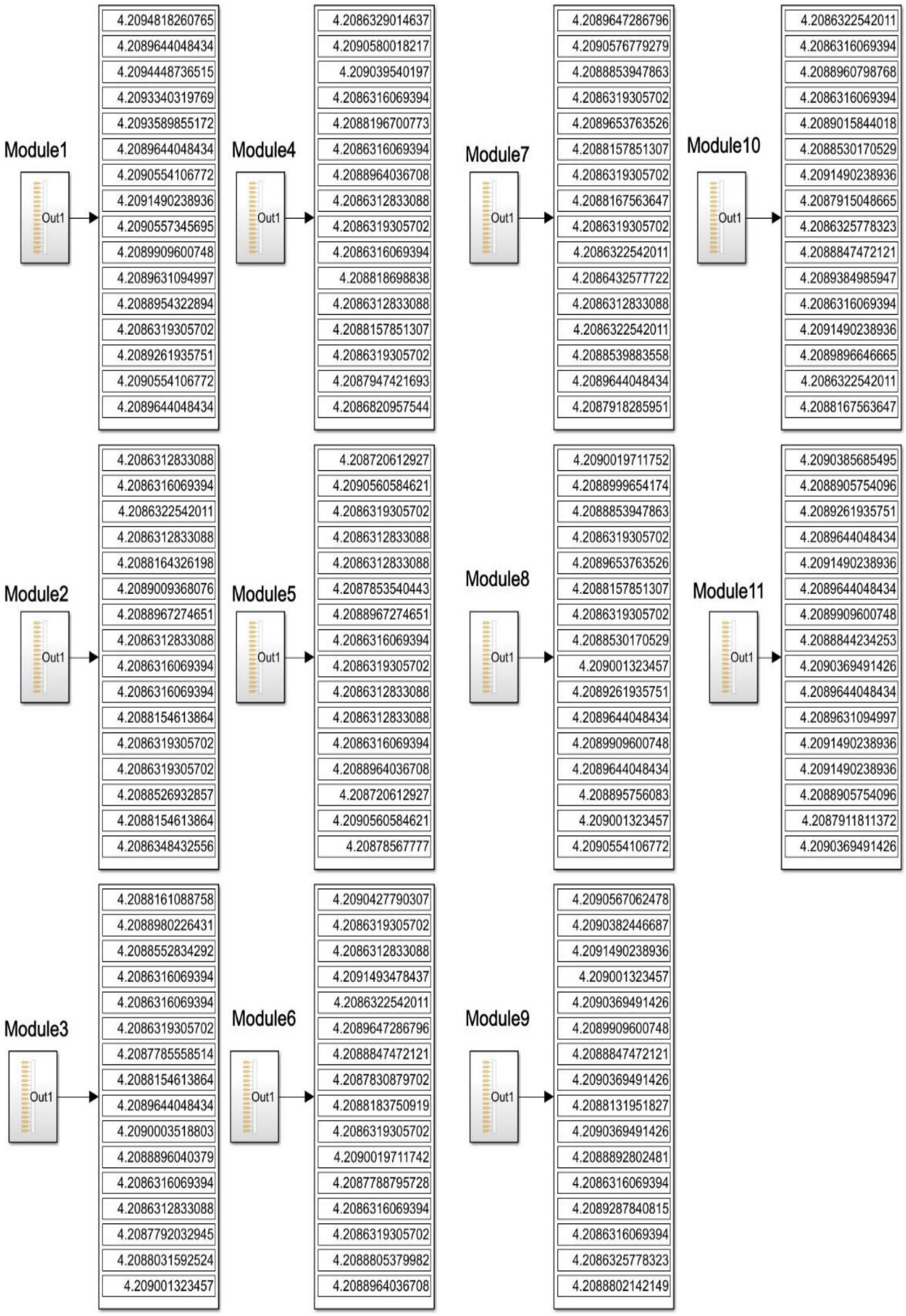

Figure 5.29. Cell voltages after balancing operation (Proposed algorithm/Case 2)

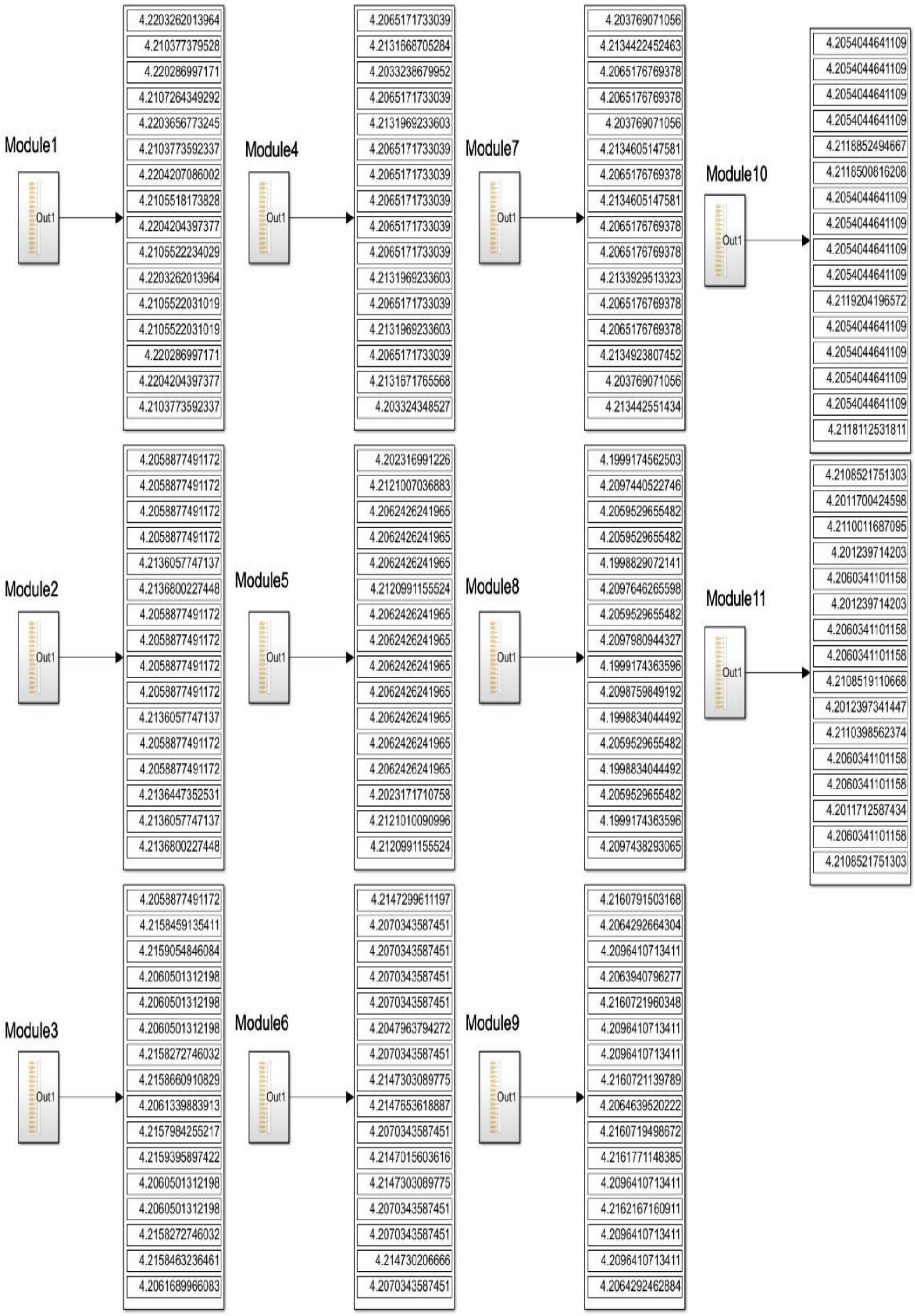

Figure 5.30. Cell voltages after balancing operation (Existing algorithm/Case 2)

Third case (last case) is tested with a simulation model that 6 out of 11 modules in the LBP have the same SOC value and initial voltage imbalance range is 64 mV. In other words, the voltage values of the battery cells in the 5 modules are different from each other. In the second case, a total of 96 battery cells had equal voltage value, but 16 cells in the same module never had the same voltage value. The difference of case 3 from case 2 is, multiple modules have the same voltage value before balancing process. The results of the last case are shown in fig. 5.31 and 5.32. As the balancing operation is completed by the proposed algorithm, the difference between the maximum and minimum cell voltage is 0.5 mV which is totally acceptable for LBPs. After completing balancing operation with the proposed algorithm, the difference between the maximum and minimum cell voltage is 0.5 mV and this result is totally acceptable for LBPs (see fig. 5.31). On the other side, as a result of balancing performed using the existing algorithm, the final difference between maximum and minimum battery cell voltages reaches 22.5 mV as shown in fig. 5.32. The balancing times of AcBS which are adapted by proposed algorithm and existing algorithm are 5316 and 12865 seconds respectively (see fig. 5.31 and 5.32). The results shown in figure 5.33 are battery cells in module 3 and are randomly selected between 11 modules. According to the result shown in Figure 5.33, the exsiting algorithm has 12865 seconds and 9.9 mV voltage imbalance in the module with 16 battery cells. However, the system designed with the proposed algorithm both balances 176 battery cells faster instead of 16 battery cells and has less imbalance in equalizing all the batteries. See figures 5.34-5.39 for more information on the active balancing results of the Case 3 study.

In short, the results shown above show that proposed algorithm is far better than the exsiting algorithm for LBPs because the developed algorithm is better at equalizing different cell voltages at the same voltage value with performing a fast balancing process. In addition, the current drawn from the vehicle battery in the balancing operation which is performed with proposed algorithm for three cases is shown in fig. 5.13, 5.22 and fig. 5.31. As the proposed algorithm works with two channels, the current in the vehicle battery is zero because the charge-discharge currents of maximum-minimum cells are paired through the CTB with each other. The proposed algorithm provide a significant improvement for the life cycle of the vehicle battery. The results of the study are summarized in table 5.5.

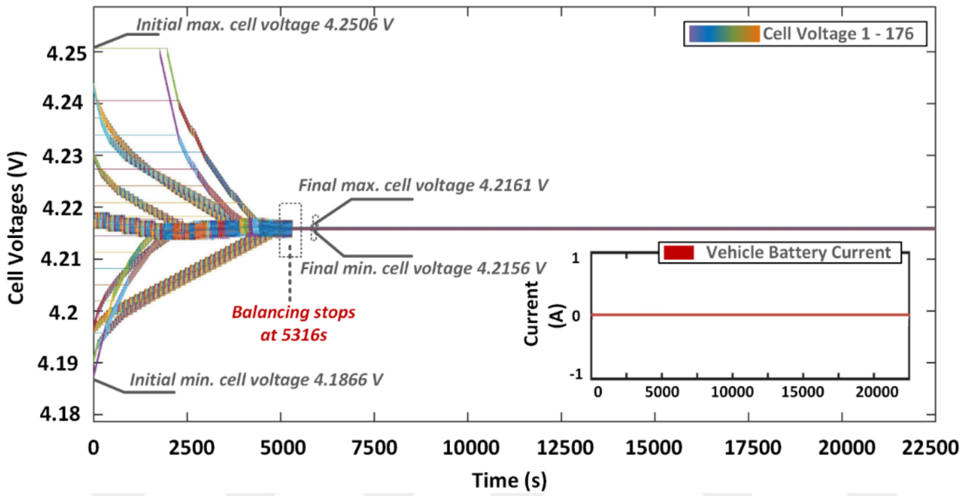

Figure 5.31. The simulation results of case 3 (Presented Algorithm)

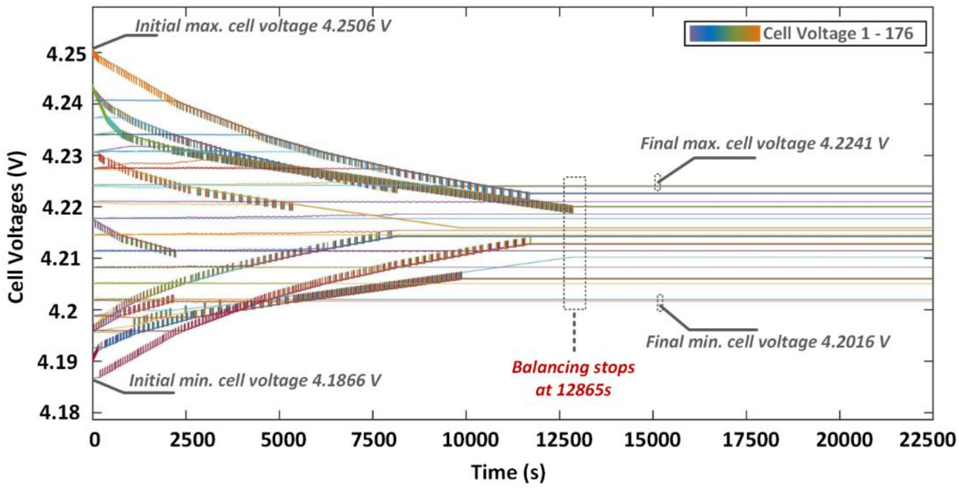

Figure 5.32. The simulation results of case 3 (Existing algorithm)

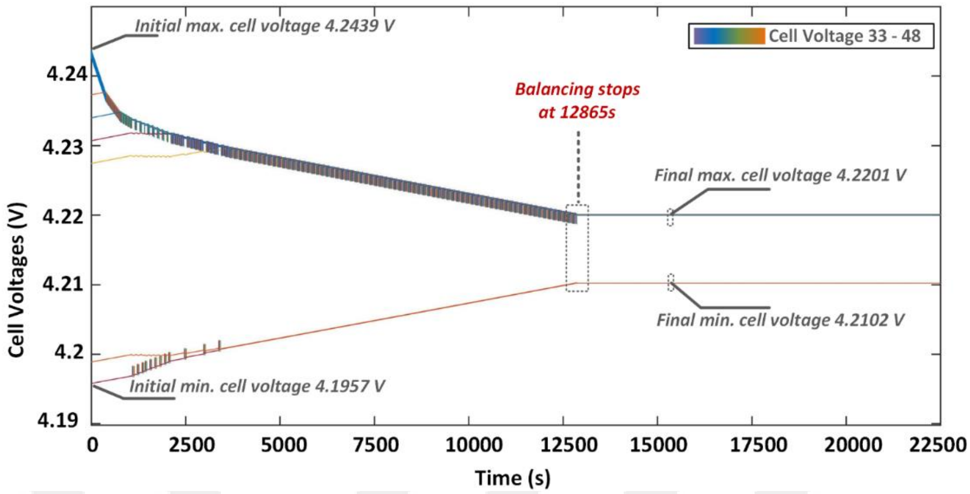

Figure 5.33. The simulation results of Module 3 /Case 3 (Existing Algorithm)

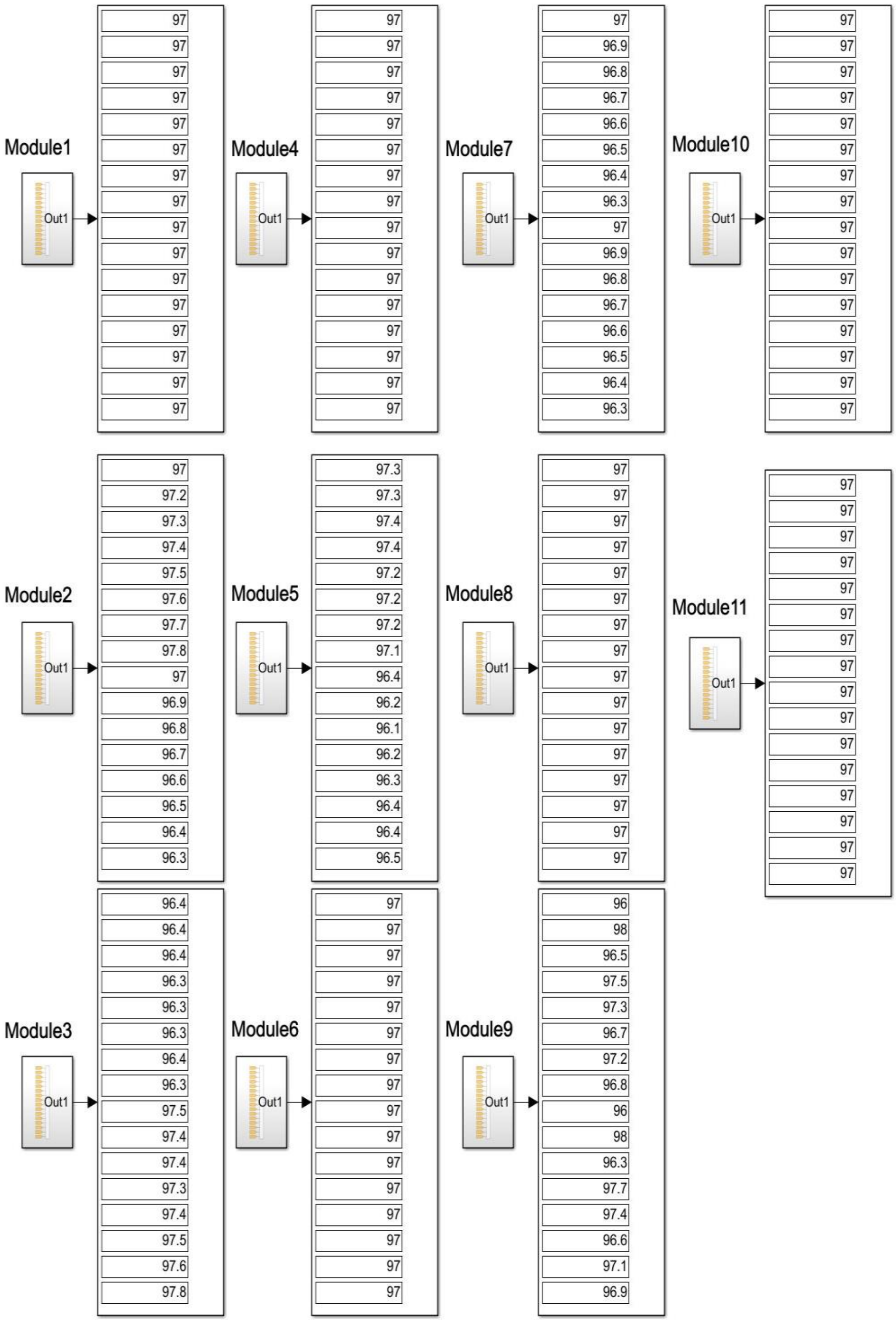

Figure 5.34. SOC levels before balancing operation (Case 3)

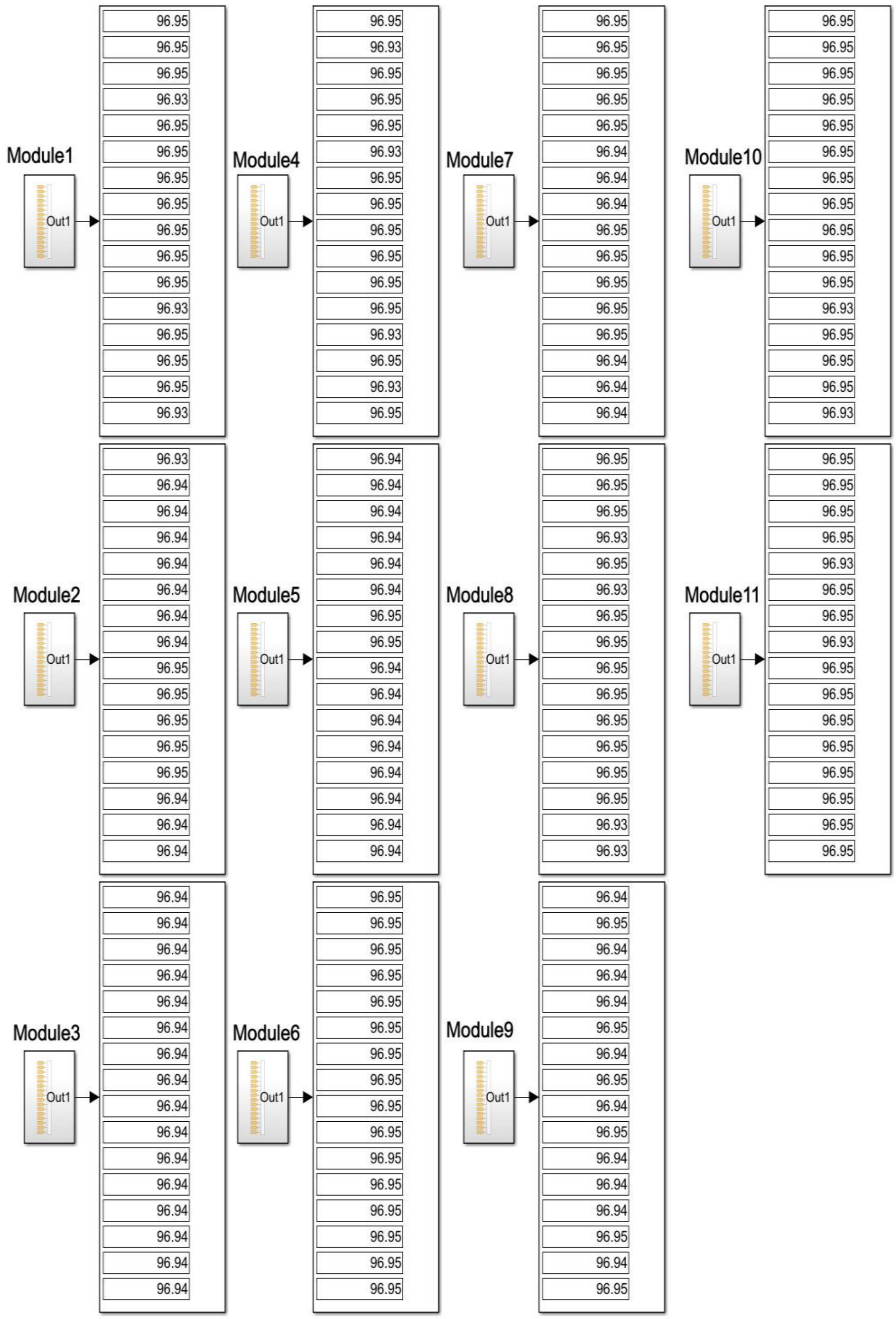

Figure 5.35. SOC levels after balancing operation (Proposed algorithm/Case 3)

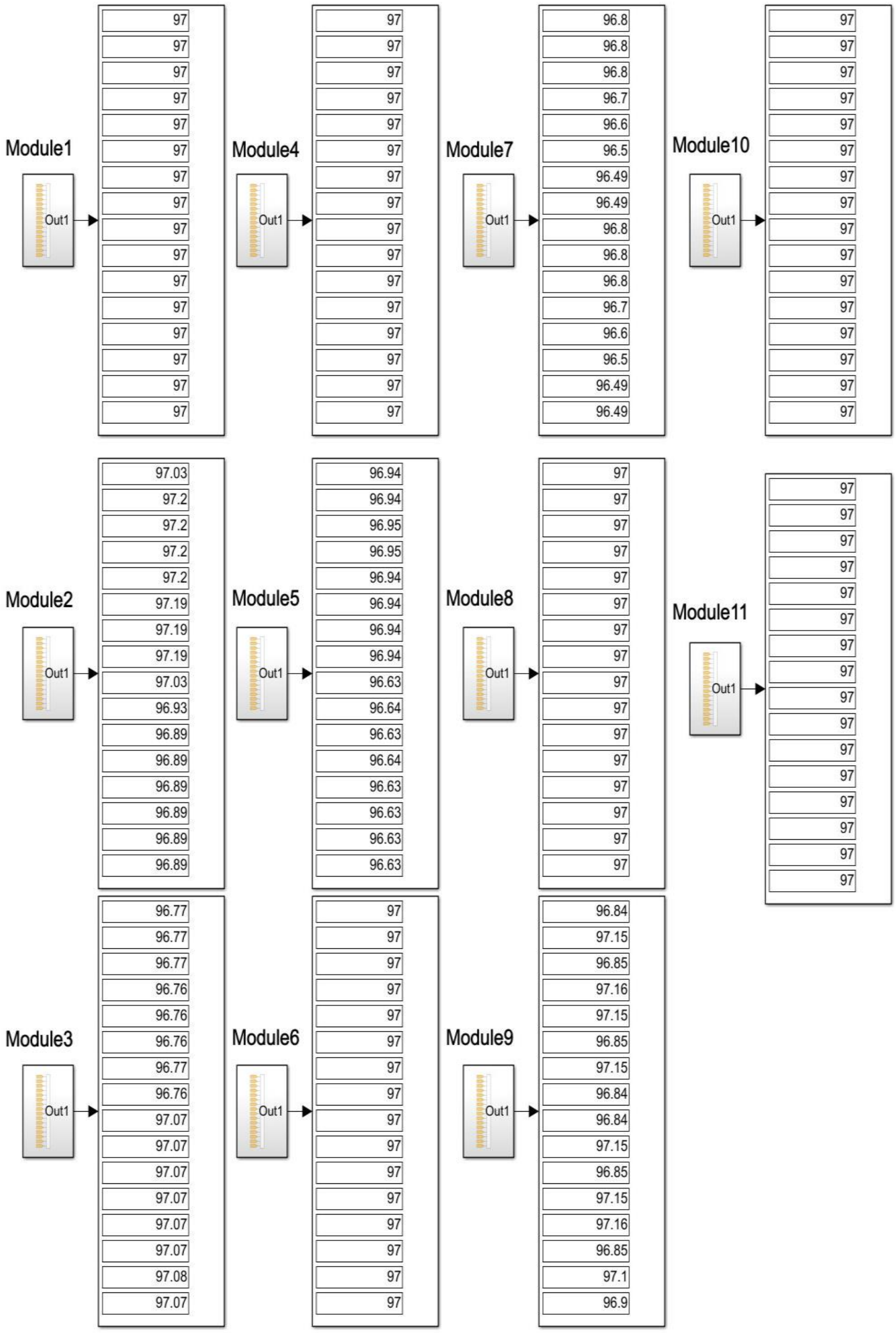

Figure 5.36. SOC levels after balancing operation (Existing algorithm/Case 3)

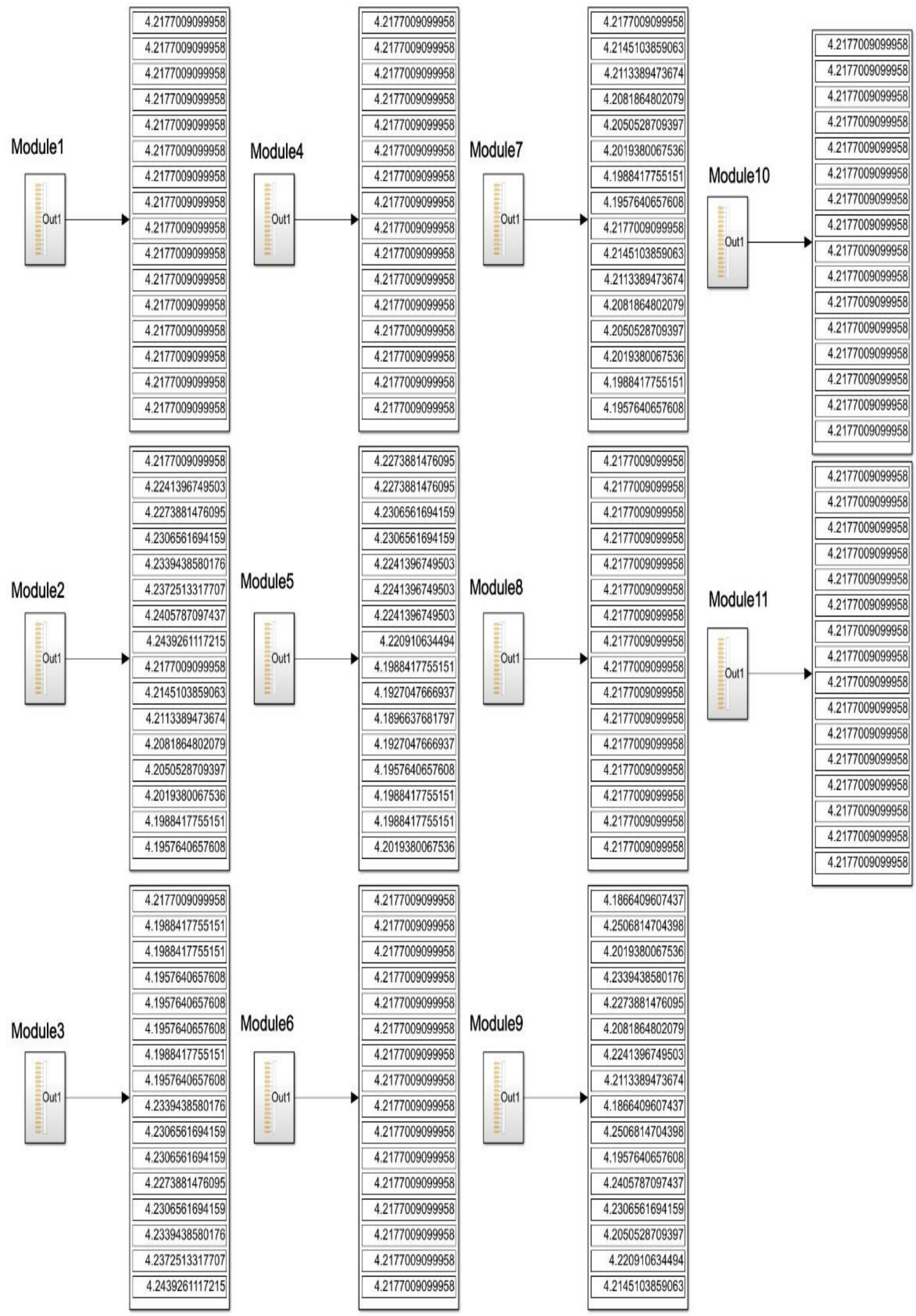

Figure 5.37. Cell voltages before balancing operation (Case 3)

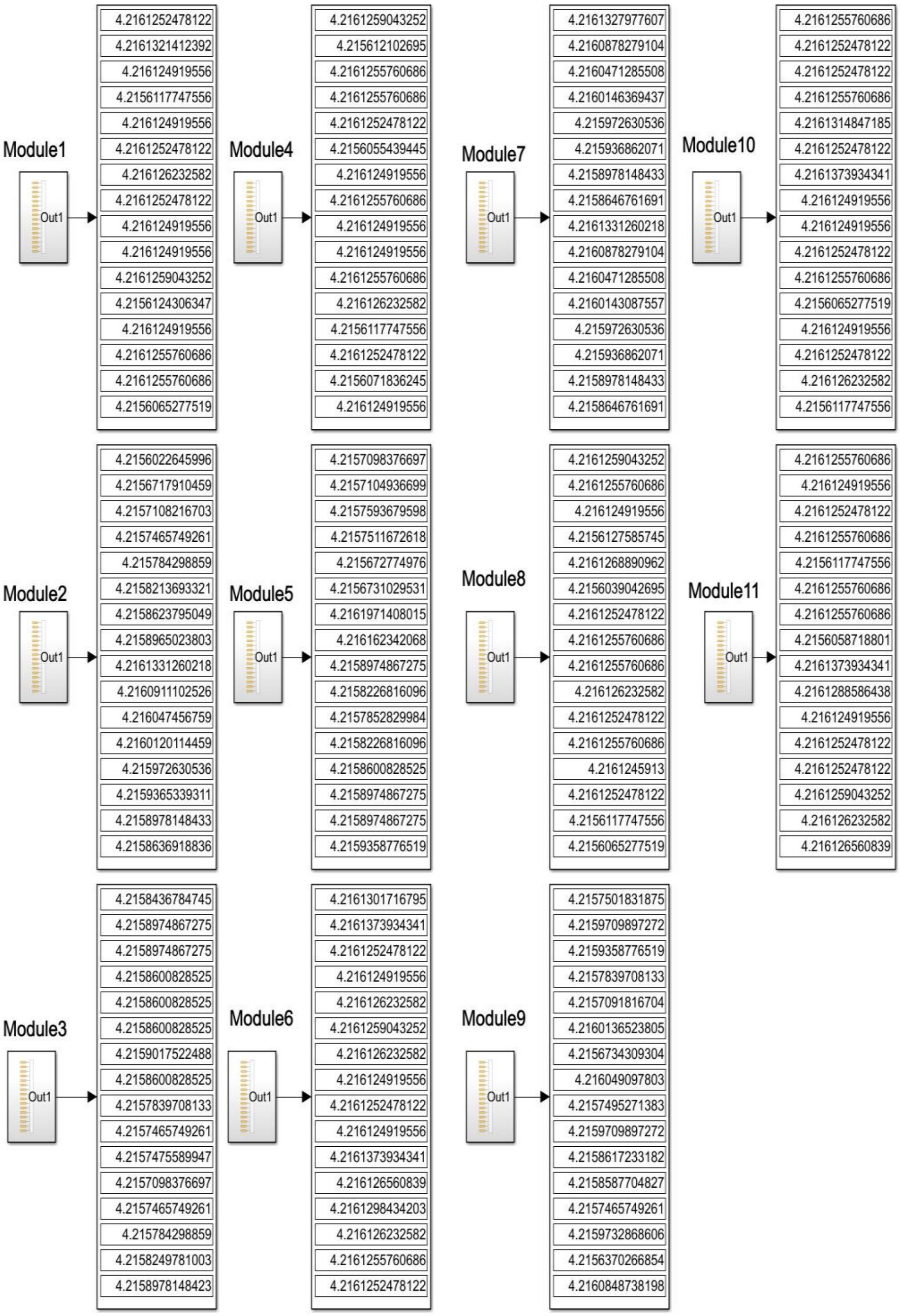

Figure 5.38. Cell voltages after balancing operation (Proposed algorithm/Case 3)

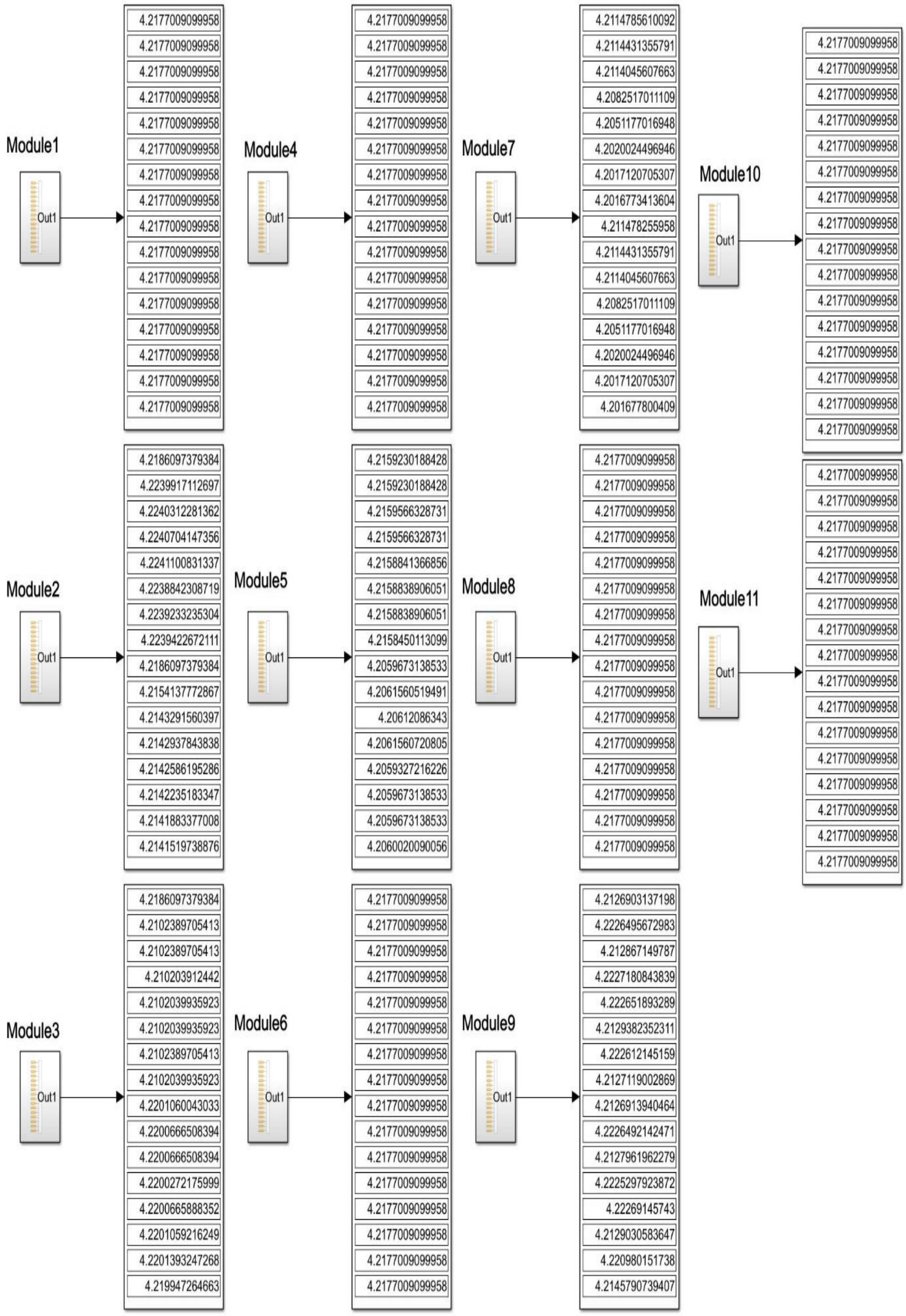

Figure 5.39. Cell voltages after balancing operation (Existing algorithm/Case 3)

Table 5.5. Summary of the study (Study 2)

	Proposed Algorithm for 176 Cells			Existing Algorithm for 176 Cells		
	Initial Voltage Difference (mV)	Final Voltage Difference (mV)	Balancing Time (seconds)	Initial Voltage Difference (mV)	Final Voltage Difference (mV)	Balancing Time (seconds)
Case 1	134	1.4	7483	134	39.3	20914
Case 2	58.3	0.8	5021	58.3	20.6	12526
Case 3	64	0.5	5316	64	22.5	12865

5.2.2.3. Study 2's Conclusion

In this thesis, a new balancing algorithm which has features such as fast balancing, simultaneous charge transfer, bi-directional power flow and charge transfer between non-adjacent cells is proposed for LBPs. When compared with existing approaches, proposed approach and existing approach have better features as seen in table 5.2. The simulation model of the AcBS which consists of switch matrix and BiDC converter for each sub-module is performed using Matlab/Simulink. To reduce run time and complexity, current sources are modeled instead of BiDC converters. Thanks to the switch rule presented in table 5.3, control signals of switch matrix is enabled when voltage imbalances occur in battery modules. The main focus of the thesis is to show the algorithm proposed in study 2 has better balancing time for LBPs than existing algorithm. The performance of the LBP is tested with two case studies by comparing two algorithms. In the first case, each sub-module of eight cells have different SOC levels while only 93 cells have different SOC levels in the second case. In conclusion, LBP designed by adapting the proposed algorithm has better results for both cases because the algorithm provides concurrent charge transfer between modules by pairing maximum and minimum cell voltages. Using vehicle battery as an auxiliary circuit can be considered as an improvement for the life cycle of the vehicle battery because vehicle battery current of proposed algorithm for both cases is zero. In short, the main aims of the thesis are; (i) to develop an algorithm that is adaptable to cell-to-cell balancing which is the cost-effective for LBPs of EHCVs, (ii) to perform fast balancing (iii) to provide multiple charge transfers simultaneously between battery modules which is crucial for EHCVs which are equipped with LBP.

6. CONCLUSION AND FUTURE WORK

EVs play significant role in daily life because of its efficient energy utilization and zero emission. Zero emission is possible in EVs because they are powered by the batteries and electric motors. The battery being the only energy storage device that has a great impact on the performance of EVs. There are different types of battery cell chemistries used in EVs but, the nominal voltage of single cell of these chemistries is very low. Battery cells are connected in parallel or in series or in a combination of both to reach high capacity battery packs. In LBP that consists of battery cells connected in series, the weakest battery cells determine the total amount of energy that can be drawn from the system. The most important reason for this is the minimum voltage limit that is put in order not to make the battery unusable. In other words, if two 5Ah charged batteries and two 10Ah charged identical batteries are connected in series, the total amount of Ah that can be withdrawn from the system is 5Ah, and there will be an unused 5Ah energy in the system. Although connecting battery cells in series solves the capacity problem, unbalance occurs both between the packages and between the cells. Battery balancing methods have been developed to solve this problem. If an ideal balancing system is to be run on identical batteries in the example given above, the charge amount of both batteries will be made 7.5Ah and the amount of energy left at the end of use will be reduced to zero. Therefore, one of the important capabilities that every battery system connected in series should have is the battery balancing system so more energy can be drawn from the batteries used with the cellular balancing system and the lifespan of these batteries will be longer. Although there are many active balancing systems in the literature which is given in chapter 4, there are not many large scale active balancing studies. The study in this thesis is designed to be used in a real EHCV. In the thesis, in order to solve the balancing problem in EHCVs, AcBC model is presented in the first study and a new balancing algorithm is proposed in the second study. Thesis's aim is to ensure that each battery cell has the same amount of energy as a result of balancing process and is an important function that should be applied in battery systems for the life and efficient use of the batteries. In the first study, an AcBC model is presented for LBP and the main objective of the presented model is to investigate system performance with different SOC values for LBP. The balancing performance of AcBC is tested with two case-studies. It is seen from the simulation results that the topology with cts which is supplied by the first four cells of the first sub-module has longer balancing time than the topology with cts which is supplied by the first cell of first sub-module. Usage of the cells as cts eliminate the need for auxiliary battery. Therefore, this approach might be considered as an improvement in existing topologies. In the second study, a new control algorithm is proposed main aims are listed as follows.

1) To develop an algorithm that is adaptable to cell-to-cell balancing which is the cost-effective for LBPs of EHCVs,
2) to perform fast balancing time
3) to provide multiple charge transfers simultaneously between battery modules

The important features that the AcBS in battery packs for EHCVs should have is having the fast balancing time and its cost should be affordable since it is a large scale circuit. Luckily, a new balancing algorithm which offers multiple charge transfers simultaneously between battery modules for LBPs that require high power application for commercial EV support these needs for AcBS. The results easily support our goals in this thesis.

For future work, an experimental prototype will be created and the proposed algorithm will be applied. Comparisons will be made with other AcBS used in LBPs of EHCVs, and the AcBC model and the algorithm will be rearranged according to the result. In this thesis, one LBP has been studied. In addition, in the future, there will be a study on active balancing between packages (parallel connected LBPs) because there is not much research on this subject in the literature and a solution that is suitable for this problem is required.

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CURRICULUM VITAE

Birand Erdoğan was born in Adana, Turkey in 1993. He graduated from Bilfen College in 2007 and Gündoğdu College in 2011. He received the license education certificate from Electrical and Electronics Engineering from Çukurova University in 2018. He started his MSc education in Electrical and Electronics Engineering in Çukurova University in 2018. He was appointed as a research assistant to the Electrical and Electronics Engineering Department of the Adana Alparslan Türkeş Science and Technology University and is currently working at the same department.

In the MSc thesis, his research areas are electric vehicles, battery balancing systems.

APPENDICES

Publication Arose Form This Thesis Work

1.International Conference Paper:

- Erdoğan, B., Savrun, M.M., Köroğlu, T., Cuma, M.U., and Tümay, M., 2019. A Fast Simulation Model for Large Scale Battery Packs Used in Heavy Electric Vehicles, 2019 3rd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT), Ankara, Turkey, pp. 1-5. DOI: 10.1109/ISMSIT.2019.8932831.